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The DEDS: DSTO's Environmental-Data Server for Research Applications

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ABSTRACT

A myriad of requirements exist within DSTO for rapid access to high-quality geospatial and meteorological data; and, with support from the Australian Defence Simulation Office, a software framework has been developed to efficiently and inexpensively serve such data for a variety of end-uses. The framework, implemented in software called the DSTO Environmental-Data Server (DEDS), includes facilities for distributed data warehousing and scheduled retrieval of published source data, as well as post-processing of data for format conversions, production of high-resolution models, and statistical analyses. Via the DEDS web interface or through its application programming interface, users can access: terrain-elevation data; historical regional-scale meteorological modelling; building-geometry data for Australian capital cities; and population-density data for Australia. Each data type is output to the user (or to the user's simulation) in a defined region with post-processing as requested by the user.

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The DEDS: DSTO's Environmental-Data Server for Research Applications

Executive Summary

Traditionally, simulations requiring environmental data have relied on idealised representations of the physical world because access to realistic modelling has been difficult to obtain and prohibitively expensive. However, low-cost data storage and computing, together with the increasing availability of public sources of geospatial and meteorological data, now offer the opportunity to economically incorporate high-fidelity environmental data in simulation products.

The authors have recognised a myriad of requirements across DSTO for environmental data and, with sponsorship from the Australian Defence Simulation Office, have developed a software framework to efficiently and inexpensively serve such data for a variety of end-uses. The framework, implemented in the DSTO Environmental-Data Server (DEDS) software, includes facilities for distributed data warehousing and scheduled retrieval of published source data. Post-processing for data-format conversions, application of higher-resolution models, and statistical analysis is also incorporated. An application programming interface permits other simulations, such as flight simulators, to communicate directly with the server to obtain streamed data; and web-based interfaces are provided to end-users for retrieval and previewing, as well as providing a system-administration capability.

The development of the DEDS was motivated by the need to provide rapid access to high-fidelity environmental models for DSTO programs and does not replace the operational weather forecasting service provided by the Bureau of Meteorology to the Australian Defence Force.

The chief outcomes of the project address several of the goals set forth in the 2011 *Defence Simulation Strategy and Roadmap*. The DEDS provides a source of environmental data and a robust interface, both of which are useable in multiple simulations. The DEDS software and stored environmental data give DSTO secure access to quality data to support simulations and permit standardisation of the manner in which environmental data is supplied. It is anticipated that other members of the Defence simulation community will be attracted to the functionality of the DEDS for this reason and because of its low cost, ease of use, and the inherently high level of verification and validation of the source data and models.

The DEDS has already been used within DSTO to contribute to several research outcomes for Defence, covering such areas as plume modelling and hazard assessment, aircraft performance analysis, and aircraft incident and accident investigation. The data and models have proven to be of high quality and fit for purpose.

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Dr. Palmer joined the Defence Science & Technology Organisation in 2007, as a member of the Air Vehicles Division. Her current work focuses on unmanned aircraft, including projects on hybrid-propulsion and power-management technologies for small surveillance aircraft and flapping-wing flight. Prior to immigrating to Australia from the US in 2004, she was employed at Lockheed Martin Missiles & Space in Sunnyvale, California, where her work involved analyses of missile systems and test failures. She earned a Ph.D. in Mechanical Engineering from Stanford University in 1997, with a thesis on the demonstration of advanced laser-based diagnostic techniques for hypersonic flows.

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John Wharington graduated from RMIT University with a PhD in Aerospace Engineering in 1999; and, after a further 6 months there lecturing, he joined DSTO in the Maritime Platforms Division. He has worked on a variety of dynamics- and simulation-related subjects, including distributed simulation infrastructures, rigid-body dynamics, hydrodynamics, and control; in applications relating to uninhabited underwater vehicles and related systems, such as towed decoys, and deployment and retrieval systems; and replenishment at sea. John is also a glider pilot and instructor and has developed several commercial instruments for gliders.

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Alex received the B.Sc. Degree with first-class honours (Applied Maths) and the Ph.D. degree in Theoretical Physics in 1987, all from Moscow University of Applied Physics and Technology. Alex has significant research and development experience in defence projects (sonar systems, turbulent flows, artificial intelligence), on which he worked in academia and industry. He joined the Defence Science and Technology Organisation in 2005, where he conducted research and development in tracer dispersion, data fusion, source backtracking and system biology. He is currently the Science Team Leader for Hazard Modelling. Alex has published more than fifty papers.

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Andrew Walker joined the Human Protection and Performance Division of DSTO in 2010. His current research focuses on simulation and modelling of physical systems including work on diffusive transport processes, complex boundaries and distributed simulation. In 2011 he graduated from Swinburne University after completing a DSTO-sponsored PhD in Mechatronic Engineering, with a thesis on 'Hard Real-Time Motion Planning for Autonomous Vehicles'.

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Andrew Robbie graduated from Melbourne University with a combined Bachelor of Engineering and Bachelor of Science in 1999, with majors in electrical engineering and computer science. Mr Robbie joined the Air Operations Division of DSTO in 1999, and works on a range of projects in the field of human-in-the-loop simulation, flight-simulator design, and the communications aspects of distributed simulation systems. His current research interests include real-time middleware systems and the design and analysis of wide-area communication networks.

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Glossary

Acronyms and Abbreviations

ABL	atmospheric boundary layer
ABS	Australian Bureau of Statistics
ADF	Australian Defence Force
ADSO	Australian Defence Simulation Office
AGL	above ground level
AMIEL	Aircraft Modelling and Integration Environment Library
ANU	Australian National University
AOD	Air Operations Division
API	application programming interface
Apr	April
Aug	August
AVD	Air Vehicles Division
BL	boundary layer
BoM	Bureau of Meteorology
CAPE	convective available potential energy
CBD	central business district
CBRN	chemical, biological, radiological, and nuclear
CFD	computational fluid dynamics
CLI	command-line interface
CPU	central processing units
CSIRO	Commonwealth Scientific and Industrial Research Organisation
C2	command and control
DCP	Defence Capability Plan
Dec	December
DEDS	DSTO Environmental-Data Server
DIS	Distributed Interactive Simulation
DSE	Defence Synthetic Environment
DSMCP	Defence Simulation Minor Capital Program
DTED	Digital Terrain Elevation Data
E	East
EGM96	Earth Gravitational Model 1996
ESRI	Environmental Systems Research Institute
Feb	February
FFI	foreign function interface
FLIR	forward-looking infrared
FY	financial year
GDA94	Geocentric Datum of Australia 1994
GFS	Global Forecasting Service
GPS	Global Positioning System
GPU	graphics processing unit
GRIB	GRIdded Binary
GUI	graphical user interface

HALE	high-altitude, long-endurance
HLA	High Level Architecture
HPPD	Human Protection and Performance Division
ID	identification number
IP	intellectual property
ISR	intelligence, surveillance, and reconnaissance
ISRD	Intelligence, Surveillance, and Reconnaissance Division
IT	information technology
Jan	January
Jun	June
Jul	July
LES	large-eddy simulation
LST	local standard time
Mar	March
MOS	model output statistics
MPD	Maritime Platforms Division
MSL	mean sea level
MSLP	mean-sea-level pressure
N	North
NCAR	(US) National Center for Atmospheric Research
NCL	NetCDF Command Language
NetCDF	Network Common Data Format
NOAA	(US) National Oceanic and Atmospheric Administration
Nov	November
Oct	October
PBL	planetary boundary layer
PNG	Portable Network Graphics
RASP	Regional Atmospheric Soaring Prediction
S	South
Sep	September
SRTM	Shuttle Radar Topographic Mission
SWIG	Simplified Wrapper and Interface Generator
S&T	science and technology
TTCP	the Technical Cooperation Program
UAS	unmanned aircraft system or systems
US	United States (of America)
UTC	universal time coordinates
V&V	verification and validation
W	West
WebREP	Web Recognised Environmental Picture
WGS-84	World Geodetic System 1984, the reference coordinate system used by GPS
WRF	Weather Research and Forecasting
WRFSI	WRF Standard Initialisation
2D	two-dimensional
3D	three-dimensional

Symbols

H_{crit}	height of critical updraft strength; variable HWCRIT in RASP/WRF output (m)
Q_c	cloud water mixing ratio; variable QCLOUD in RASP/WRF output (kg/kg)
Q_v	water-vapour mixing ratio; variable QVAPOR in RASP/WRF output (kg/kg)
u	velocity component in the x-direction; variable U in RASP/WRF output (m/s)
u_*	friction velocity in Monin-Obukhov similarity theory used to provide 1st-order closure in PBL-parameterisation model; variable UST in RASP/WRF output (m/s)
v	velocity component in the y-direction; variable V in RASP/WRF output (m/s)
w	velocity component in the z-direction; variable W in RASP/WRF output (m/s)
w_{BL}	BL maximum up/down motion; variable WBLMAXMIN in RASP/WRF output (m/s)
W^*	thermal updraft velocity; variable WSTAR in RASP/WRF output (m/s)
x	coordinate measuring distance in the longitudinal (East—West) direction, positive in E-direction (m)
y	coordinate measuring distance in the latitudinal (North—South) direction, positive in N-direction (m)
z	coordinate measuring distance in the vertical direction, positive in the upwards direction (m)

Units

arcsec	arcseconds
°C	degrees Celsius
ft	feet
GB	gigabytes
hr	hours
J	Joules
K	Kelvin
kg	kilograms
km	kilometres
kt	knots
m	metres
MB	megabytes
min	minutes
mm	millimetres
Pa	Pascals
rad	radians
s	seconds
TB	terabytes
W	Watts

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1. Introduction

1.1 Overview

Simulations requiring atmospheric representations, including those for the prediction of chemical, biological, radiological, and nuclear (CBRN) dispersion, aircraft flight behaviour, and acoustic propagation, have often relied on simplified or idealised models: the atmosphere has usually been treated as temporally and spatially uniform [1]. Access to meteorological modelling has been complex and prohibitively expensive; and high-quality information about other aspects of the physical world (*e.g.*, population-density distributions and terrain data) has also been difficult to source and to provide seamlessly to simulations. However, low-cost data storage and computing, together with the increasing availability of public sources of geo-spatial and meteorological data, now offer the opportunity to economically incorporate high-fidelity environmental data in simulation products.

The authors have had involvement in several projects for which accurate representations of the physical environment were needed; furthermore, they recognised myriad other requirements across DSTO for environmental data. Thus, development was undertaken of server software, the DSTO Environmental-Data Server (DEDS), that is capable of efficiently and inexpensively providing such data for a variety of end-uses, including real-time simulations, constructive simulations for performance and operations analysis, and historical analyses.

The DEDS provides high-fidelity terrain data, population-density data for Australia, and building-geometry data for Australian capital cities. Regional (mesoscale) weather modelling is also available in a hindcasting mode in which a past day or period is examined either as an historical record or in a statistical sense in which "typical" conditions are evaluated. Specialist knowledge of meteorological modelling is not needed to operate the system or to utilise its output.

The DEDS includes facilities for distributed data warehousing as well as scheduling of retrieval of published source data. Post-processing for coordinate-system and other data-format conversions, application of higher-resolution models, and statistical analyses is also incorporated in the scheduling system. An application programming interface (API) permits users to retrieve remotely stored data as well as data cached locally. A web-based graphical user interface (GUI) is also provided for retrieval and previewing, as well as for system administration.

1.2 Project History

In 2007, the weather-modelling techniques now utilised by the DEDS were implemented in a stand-alone form by the Maritime Platforms Division (MPD) and the Air Vehicles Division (AVD) for a study of the performance benefits achievable for small, tactical unmanned aircraft systems (UAS) through the use of autonomous thermal soaring [2]. During financial year (FY) 2008/2009, weather modelling based upon that methodology was incorporated into a broader environmental-modelling system (now known as the DEDS) by Human Protection and

Performance Division (HPPD) personnel under a Defence Simulation Minor Capital Program (DSMCP) project, funded by the Australian Defence Simulation Office (ADSO) and entitled 'Development of New Modelling Capabilities for the CBR Virtual Battlespace'.

The outcomes described in this report are the product of the previous DSMCP project and a 2009/2010 DSMCP project entitled 'Environmental-Modelling Infrastructure for Defence Applications', conducted by AVD, MPD, and the Maritime Operations Division. This project added significant functionality and improved user and programming interfaces to the software and resulted in the creation of user and developer documentation [3]. The software was also packaged and documented such that a competent information-technology (IT) administrator may independently install and maintain a duplicate server [4], as may be required for analyses involving classified or commercially sensitive applications of the data.

An additional capability aimed at modelling microscale weather phenomena and creating graphical representations for use in, for example, flight simulators was developed under a 2010/2011 DSMCP project by Air Operations Division (AOD) personnel with contractor assistance. Some aspects of the resulting software are described in this report, though the details are left to future reporting.

1.3 Defence Context

1.3.1 Relevance to the *Simulation Strategy and Roadmap*

The chief outcomes of the present work address several of the goals set forth in the 2006 *Defence Simulation Roadmap* [5] and in the subsequent 2011 *Defence Simulation Strategy and Roadmap* [6]. The DEDS software and stored environmental information provide DSTO secure access to high-fidelity data to support simulations; and its interface permits standardisation of the manner in which environmental data is supplied to simulations across DSTO Divisions. The DEDS therefore meets the aim stated in the 2011 *Defence Simulation Strategy and Roadmap* [6] of:

> management and re-use of … underlying data and component models that might be integrated and assembled into new simulations.

It is anticipated that other members of the Defence simulation community will be attracted to the use of the DEDS because of its low cost and ease of use. In addition, end-users will likely value the inherently high level of verification and validation (V&V) of the source data and models employed by the DEDS. This requirement for future simulation is highlighted in the 2011 *Strategy and Roadmap*, as follows:

> As well as availability, data provenance, integrity and management are required to ensure the appropriateness of data for simulation purposes. Complete and accurate data is vital in providing effective simulation support to decision making.

1.3.2 Complementary Modelling Systems

1.3.2.1 BLUElink and the Defence Synthetic Environment

No system equivalent to the DEDS is known by the authors to exist within DSTO or Defence, nor is one commercially available. BLUElink [7], developed by the Royal Australian Navy, the Bureau of Meteorology (BoM), and the Commonwealth Scientific and Industrial Research Organisation (CSIRO), delivers ocean forecasts for the Australian region and has some overlapping features with the DEDS; however, it is unable to satisfy the requirements that the DEDS was designed to meet.

The fact that BLUElink and the DEDS focus on different aspects of the physical environment, while having a degree of commonality, means that they could form complementary elements of a broader Defence modelling capability. This, indeed, is embodied in the ADSO Defence Synthetic Environment (DSE) Baseline Program [8, 9], in which both simulations are potential components of an enterprise-wide modelling and simulation structure. The DSE is intended to support training, capability development (experimentation), and operations with integrated, reusable tools in a common framework that can serve as the foundation to meet Defence end-user requirements [10]. Furthermore, the DSE will provide "an authoritative repository of simulations, environmental and entity models, together with capability governance tools" [6].

1.3.2.2 WebREP

The *Defence Capability Plan* (*DCP*) *2006–2016* [11] and subsequent updates to the *DCP* [12, 13] have recognised that knowledge of the physical environment is crucial in military operations. *DCP 2006–2016* states that:

> [k]nowledge of the environment is a critical factor in the conduct of successful joint military operations. … The provision of reliable and relevant geospatial and environmental data facilitates comprehensive situational awareness and decision superiority in the battlespace environment, and enables the optimal employment of platforms, weapons systems and sensors.

Project JP 1770 Phase 1 (Rapid Environmental Assessment) [11] has the aim of enabling "a comprehensive and thorough understanding of the physical maritime operating environment and its likely impact on military operations". In response to this requirement, a web-based environmental- and geospatial-information management tool called the Web Recognised Environmental Picture (WebREP) has been developed [14]. WebREP is intended to permit active assessment of environmental conditions and distribution of that information in real-time. Its operational context thus differs significantly from that of the DEDS; however, the regional-atmospheric modelling capability developed for the DEDS may be useful as a prototype that could be incorporated (in a forecasting capacity) into WebREP or a system such as BLUElink.

1.3.2.3 BoM Forecasting Services

DSTO's development of a weather-modelling capability was motivated by the need to provide rapid access to high-fidelity environmental models for DSTO programs and other potential Defence uses. The DEDS was not designed or intended to replace the operational weather-forecasting service provided by the BoM [15] to the Australian Defence Force (ADF). The BoM also provides a source of weather forecasting data that is used by Land Division (former HPPD) personnel, output from CSIRO's Conformal-Cubic Atmospheric Model [16]; and their interaction has been unaltered by the development of the DEDS.

1.3.3 US Army Weather Simulation

The US Army has long pursued the inclusion of accurate environmental models in simulations of command and control (C2), weapons, and sensor systems for intelligence, surveillance, and reconnaissance (ISR) [1, 17]. Shirkey [1] encapsulates the need for weather data and the challenges of its implementation in simulations as follows:

> Applying weather to simulations is always problematic – detailed physics calculations are frequently required that involve significant amounts of computer time; even the simplest of atmospheric calculations frequently takes too long. Weather, however, is an important factor in determining the course and outcome of real battles. [It affects] virtually all battlespace functional areas from logistics and maneuver to C2 & ISR and combat engagements. Environmental data such as aerosol type, solar insolation, albedo, terrain elevations, soil moisture, accumulated snow cover, and other meteorological parameters are examples of the basic parameters that characterize the environment. However, to be useful in simulations, these data must be transformed into features, effects and impacts. Included in this area are other features (clouds, fronts and thunderstorms, *etc.*), weather effects such as illumination, thermal emission, scattering and propagation losses that drive target contrast changes, and weather impacts that broadly describe the general environmental limitations on performance. Thus weather, atmospheric transport and diffusion processes, and the attenuating effects of the environment on the propagation of electromagnetic energy all impact target acquisition and high technology weapons performance. Converting these meteorological parameters and weather features into quantitative effects and impacts that are not computationally burdening for simulations is a difficult proposition. Not to be forgotten are high level simulations that deal with aggregated units. These simulations simply can not [*sic*] afford the computational burden that calculations for atmospheric effects on individual platforms and systems frequently require.

The weather-modelling output delivered by the DEDS and the capability it provides to distribute environmental data to other simulations address some of the difficulties described by Shirkey. Additional modelling capabilities, in the form of stand-alone simulations relying on its output, would be required, however, to provide seamless assessments of the impact of weather conditions on platforms, C2, weapons, and sensors.

1.4 Applications

Software supporting two significant simulation capabilities was developed through the project conducted in FY 2009/2010: (1) aircraft flight simulation and (2) modelling of acoustic transmission from airborne sources. These developments resulted in the availability of high-fidelity meteorological and terrain data as components of the Aircraft Modelling and Integration Environment Library (AMIEL) [18], developed by Aerospace Division (former AVD) scientists and utilised across DSTO for flight simulation, and as input for high-resolution acoustic-modelling software packages, supplied for use in the project via the Technical Cooperation Program (TTCP). Both applications necessitated the incorporation of specific data formats and interface features into the DEDS software.

In each case, the use of realistic environmental conditions will enhance the validity of the simulation and is a necessity for some common applications, including:

- investigations of aircraft incidents and accidents in which weather and/or terrain have played a significant role;
- statistical evaluations of aircraft performance under the influence of weather conditions (*e.g.*, endurance or sensor capabilities of surveillance aircraft in a specific global location during a particular season or month);
- investigations of environmental (solar- and wind-) energy harvesting by tactical UAS with the aim of improving their range and endurance by enabling the use of electric propulsion; and
- predictions of acoustic signatures from fixed- or rotary-wing aircraft, which are known to be sensitive to atmospheric and terrain conditions.

The data and processing methods provided by the DEDS also remain useful for the work of the Modelling, Analysis, and Physical Sciences Group within Land Division, who model contaminant dispersion and support incident-response teams. Meteorological information is a critical input for modelling and simulation of accidental or malicious releases of hazardous materials in the atmosphere. Modern turbulent-dispersion models require such input as an initial condition to predict the propagation of CBRN plumes through non-uniform terrain and urban settings. An integrated modelling framework, coupling meteorology with dispersion models and terrain, building-geometry, and population-density data, is a valuable tool for the evaluation of various 'what-if' CBRN scenarios, which are important for operational planning, risk mitigation, and consequence management. This approach is widely used by the ADF and by the community of first responders.

The extensive, high-fidelity meteorological dataset provided by the DEDS (for a given region, date, and time) serves to reduce the uncertainties of CBRN-modelling. The consistent application of the available meteorological-data repository may result in the enhancement of the predictive capabilities of CBRN-dispersion models used operationally. Meteorological, terrain, and building-geometry data output by the DEDS has already been used, along with third-party software, to model complex airflows in built-up areas [19, 20]. Such simulations are useful for studies of micro-UAS performance as well as for CBRN-threat assessment.

Another recent example of an application of the DEDS was scientific support provided by DSTO to the Royal Australian Air Force Directorate of Defence Aviation and Air Force Safety

following a fatal helicopter accident [21, 22]. Output from the DEDS provided an understanding of the meteorological conditions at the time and place of the accident (and at those of several related hazardous occurrences); and a statistical analysis of the weather conditions helped investigators identify its likely root cause. The terrain data supplied by the DEDS was also used to verify that the weather modelling was performed in the correct region and that land features were represented correctly, as they had a significant impact on the meteorological conditions.

1.5 Structure of Report

The DEDS framework is described in §2, which also provides information about the external data sources used as raw inputs and the processing that is performed by the DEDS before data is delivered to end-users. A brief illustration of an application, a performance analysis of a small, electrically powered tactical UAS in a specific region, is provided in §3. The results demonstrate just one of the many uses of the environmental-modelling data provided by the DEDS. The future use, maintenance, and possible extensions of the software and datasets are discussed in §4, where recommendations are also made about the course of action to be followed if modifications or updates to the source data are desired. In §5, the capabilities of the DEDS and its implications as a Defence asset are summarised.

2. Server Description

2.1 User Interface

The basic functionality of the DEDS software is described in this section. End-users are referred for detailed information to the user's guide [23]; and administrators wishing to install a new instance of the DEDS software or to perform system maintenance and upgrades are referred to the installation guide [4].

2.1.1 Home Page

The Home page of the DEDS web-based GUI is shown in Figure 1. The page provides information about the DEDS, the services offered, the raw data available, and the status of the system, including the disk space available for raw and processed data and any tasks being

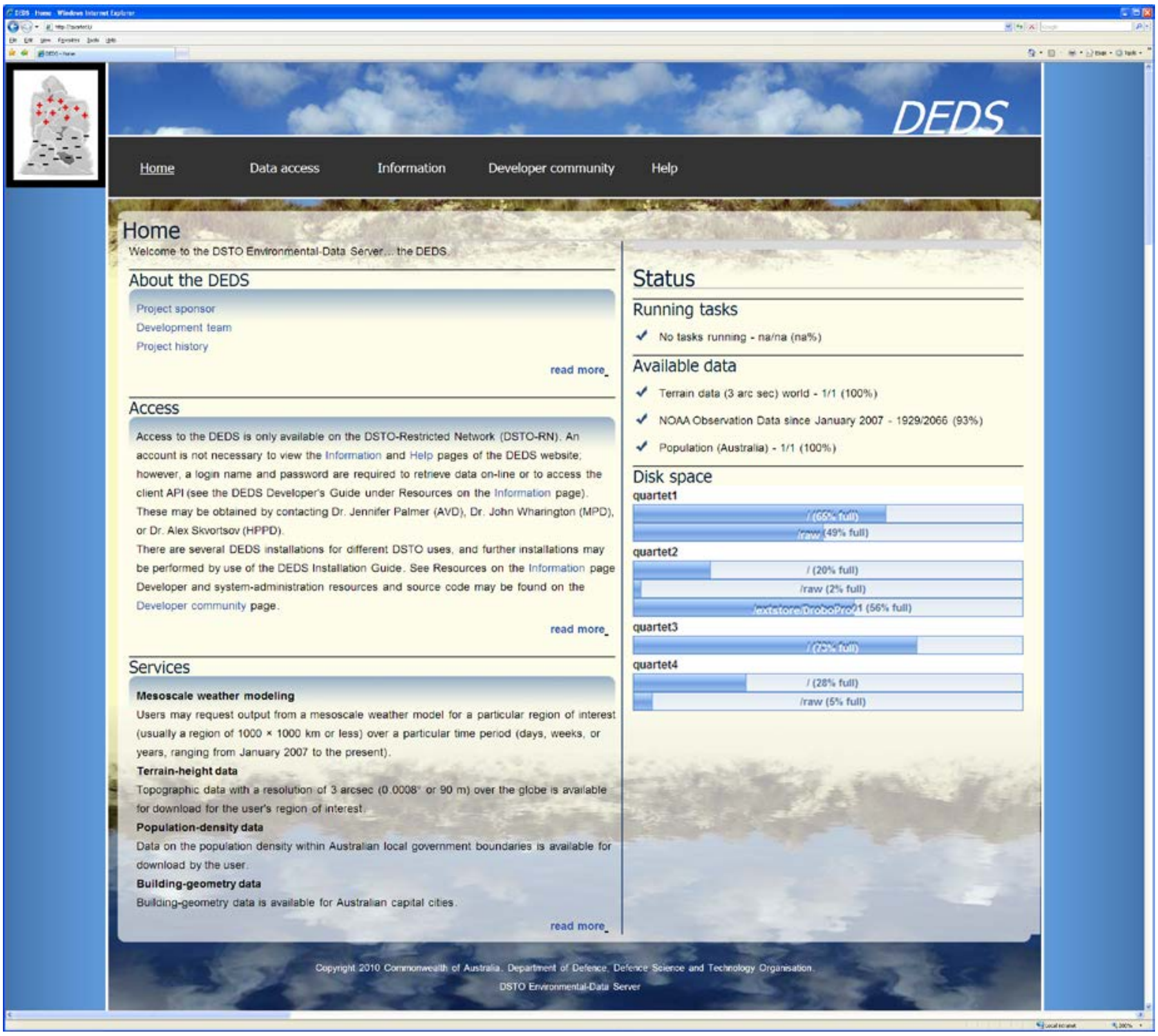


Figure 1 Screenshot of the DEDS Home page

performed. Links from the DEDS Home page provide users and administrators with the ability to:

- request data within a particular region and (for weather modelling) for a particular time period;
- monitor tasks associated with data requests;
- retrieve processed data;
- perform statistical and other types of analyses on processed data using scripts; and
- perform administrative tasks.

Clients without physical access to the server may access it through the DSTO network, as well as uploading scripts and executing analyses on the server.

2.1.2 Region and Data-Type Specification

A user may request mesoscale meteorological, terrain-height, building-geometry, or population-density data for a specific region through the DEDS GUI or API. A screenshot of the GUI for region selection is provided in Figure 2. A region is a rectangular area of the Earth defined by latitudinal- and longitudinal-coordinate limits. Additional information that is stored on a regional basis includes time zones, locations of geographic points of interest, and spatial and temporal parameters selected by the user and dependent on the type of processing that has been requested. User-defined regions are the fundamental mechanism for constructing environmental-data queries on the DEDS; and the DEDS maintains a list of geographic regions from previous data retrievals, for on-going processing or for re-visiting by the user at a later date. The highlighted regions in Figure 2 are those for which modelling has been performed for research purposes or for testing of the system during its development (*e.g.*, Arizona and various Australian regions).

Results from the DEDS are geo-referenced datasets, guaranteed to encompass the area requested by the user. This means that the data is self-describing with regard to the information needed by the end-user to perform analyses. This facilitates selection of appropriate subsets of environmental data.

2.1.3 Process Monitoring and Data Retrieval

The DEDS includes three sets of tools for process monitoring and data retrieval: command-line tools, an API, and the web-based GUI.

A collection of tools is available through a command-line interface (CLI) for users logged onto the DEDS server. Users can initiate or halt tasks with these tools, and they can inspect the outputs and log files of tasks. Administrative tasks related to a DEDS installation are also enabled. The administrative tools are low-level and primarily useful to IT administrators. They permit some functions, such as clearing error messages, that are deemed unnecessary for general users and thus are only exposed at the system-administration level.

The second tier of tools is accessible via the DEDS API. These tools are used to start, stop, and query the status of user-requested tasks, as well as permitting users to access data products.

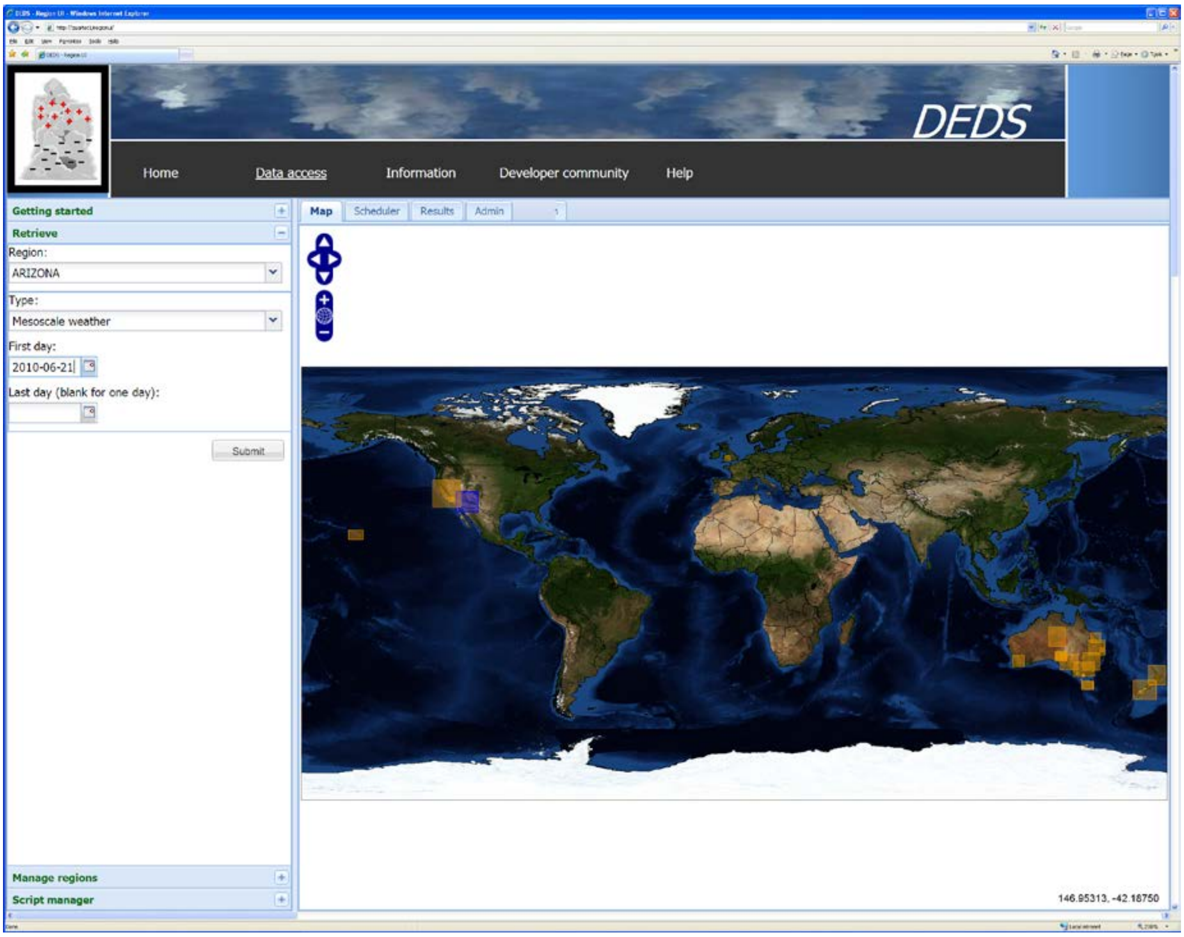


Figure 2 Screenshot of the map window on the DEDS Region-interface page, through which a user specifies a region and data type for retrieval (in this case, mesoscale weather modelling for the US State of Arizona over the period of the Summer solstice of 2010)

The implementation of the API is focussed on minimising the time required for single queries; thus, it provides process monitoring on a task-by-task basis. The API also allows DEDS functionality to be embedded in third-party applications (*e.g.*, AMIEL-based flight simulations) without requiring users to manually source data from the DEDS via the CLI or web GUI.

The final tier of tools is accessible via the DEDS web interface (its GUI). The user may create regions and initiate tasks through the interface window shown in Figure 2. These tasks include the provision of high-resolution terrain-height data, population-density data, building-geometry data, and mesoscale weather-hindcast data within the user's region of interest. In addition, a user may request the output of meteorological conditions in the form of a vertical sounding or high-resolution terrain data appropriate for input to acoustic-modelling software packages (or both). The web GUI also includes pages that show queued, active, and completed data retrieval tasks and provides a convenient way to inspect results and log files, as shown in Figure 3.

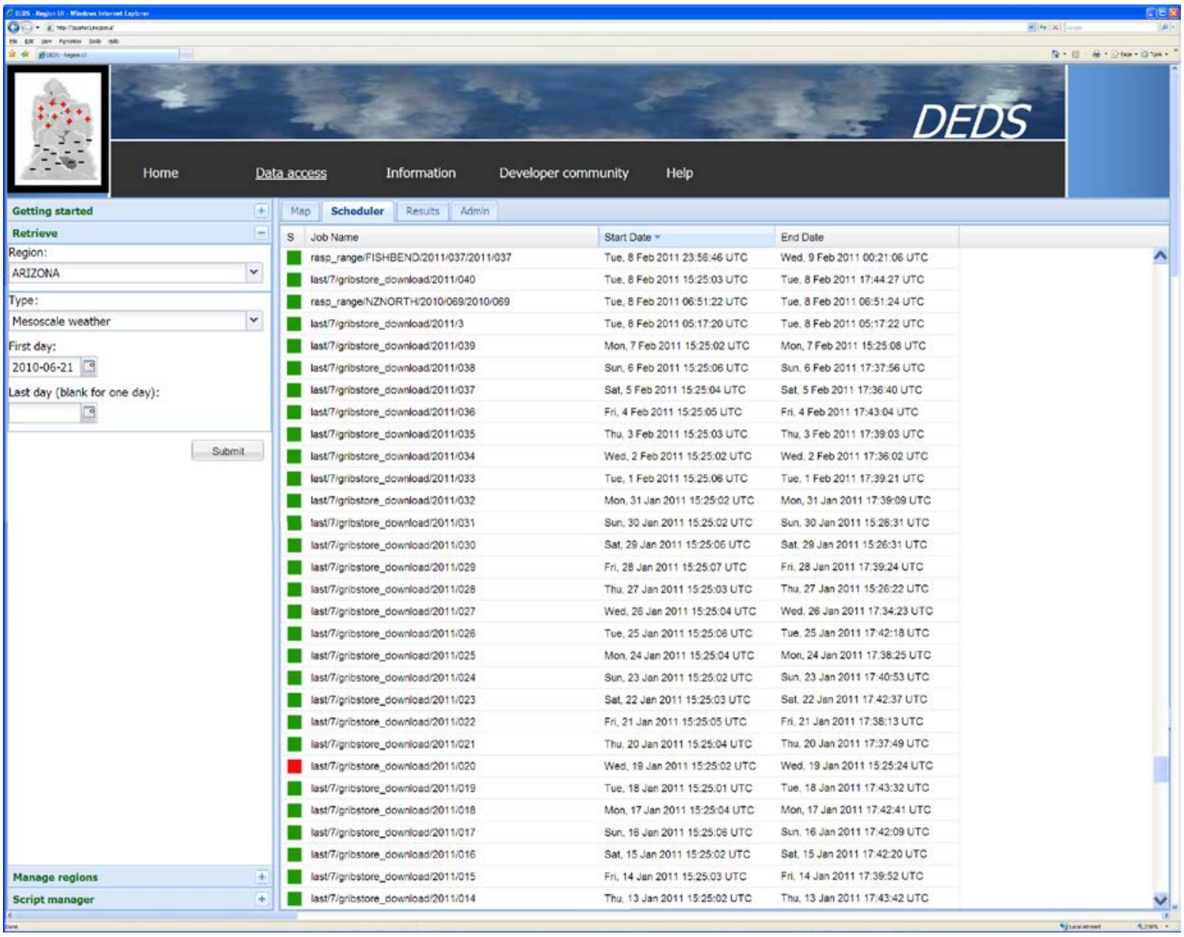


Figure 3 *Screenshot of the scheduler window on the DEDS Region-interface page, in which the user may monitor the status of his request*

Access to the DEDS is permitted via the API and GUI with a common REST interface [24], an architecture commonly used in web-based applications. This allows aspects of the DEDS software directly related to its server capabilities to be tested as a single component and ensures that the implementation of future extensions or additions related to process monitoring and data retrieval are as simple as possible.

A final approach to process monitoring involves the automatic processing of mesoscale hindcasts on user-requested regions whenever new global meteorological data (§2.2.2.1) is downloaded. This has two effects: firstly, it reduces the latency in data retrieval for end-users who regularly access meteorological data; and, secondly, it provides a mechanism for an end-user to verify that the DEDS is functioning as expected.

2.1.4 Data Analysis

Statistical analyses of weather patterns in a specific region of interest and their effects on platform and sensor performance and vulnerability may be executed on the server via the CLI. The DEDS software permits users to upload scripts written in the Perl language to perform

such analyses. One of the benefits of this strategy is that rather than downloading and handling large quantities of weather data, analyses may be performed at the site of the data and only the results downloaded.

An example of one type of statistical analysis that may be performed by use of the meteorological modelling capabilities of the DEDS is provided in §3.

2.2 Data Sources and Processing

2.2.1 Terrain Height

2.2.1.1 Sources

High-quality terrain-height data collected during the Shuttle Radar Topographic Mission (SRTM) [25] is available from several sources. The raw SRTM data covers approximately 80% of the globe, with many voids, regions in which inconsistent or null returns were received. Voids tend to occur over bodies of water, sand deserts, and regions with extremely steep elevation gradients. The region of the Himalayas has the greatest concentration of voids in the original data. The vertical uncertainty for the dataset is estimated to be about 16 m. Several versions of the SRTM dataset, with void-filling and other corrections applied, are available; and these vary in terms of the types of errors that are present.

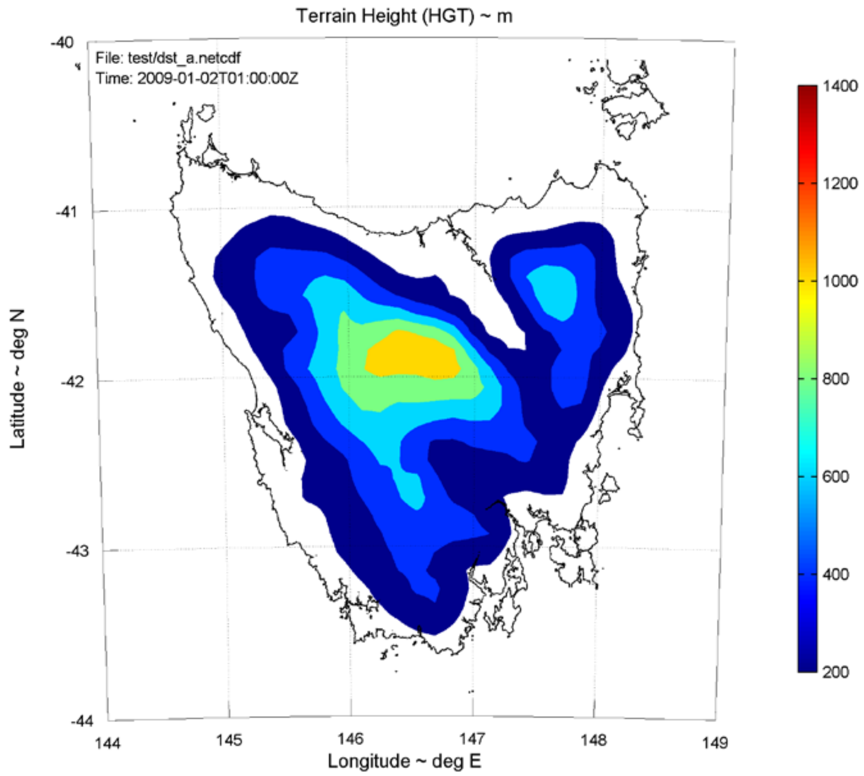
The primary terrain-elevation dataset available to users via the DEDS is based on post-processed SRTM data (SRTM Version 3.2 or, here, simply SRTM3) [26], which is in the form of geoTIFF image files [27] having a spatial resolution of 3 arcsec (or approximately 90 m at the equator [28]). This dataset has undergone validation against other sources of terrain information [29]. Improvements to the quality of the processed data have been the subject of significant research worldwide, and its limitations are well understood [30]. Where appropriate, the overall quality of the terrain dataset for the DEDS was improved through the use of additional data, including 90-m-resolution elevation maps from Geoscience Australia [31].

When a user retrieves terrain data in geoTIFF format from the DEDS, SRTM3 data is provided at full resolution; however, lower-resolution terrain data, with a grid spacing of 30 arcsec, is used in the mesoscale weather modelling produced by the DEDS (§2.2.2). Figure 4 provides a comparison between the low- and high-resolution terrain data used by and available from the DEDS, in this case for Tasmania; and Figure 5 shows DEDS terrain data for the region around the city of Melbourne. The high-resolution terrain shown in Figure 4(b) and in Figures 5(a) and (b) has been displayed at a resolution of 0.002°, rather than at the full resolution available from the DEDS (0.000833° or 3 arcsec), because of the large size of the dataset covering these regions.

2.2.1.2 Conversions

CBRN-hazard modelling, an important application of the DEDS [19, 20, 32], relies on software packages [33, 34] that typically require the input of data in the Digital Terrain

(a)



(b)

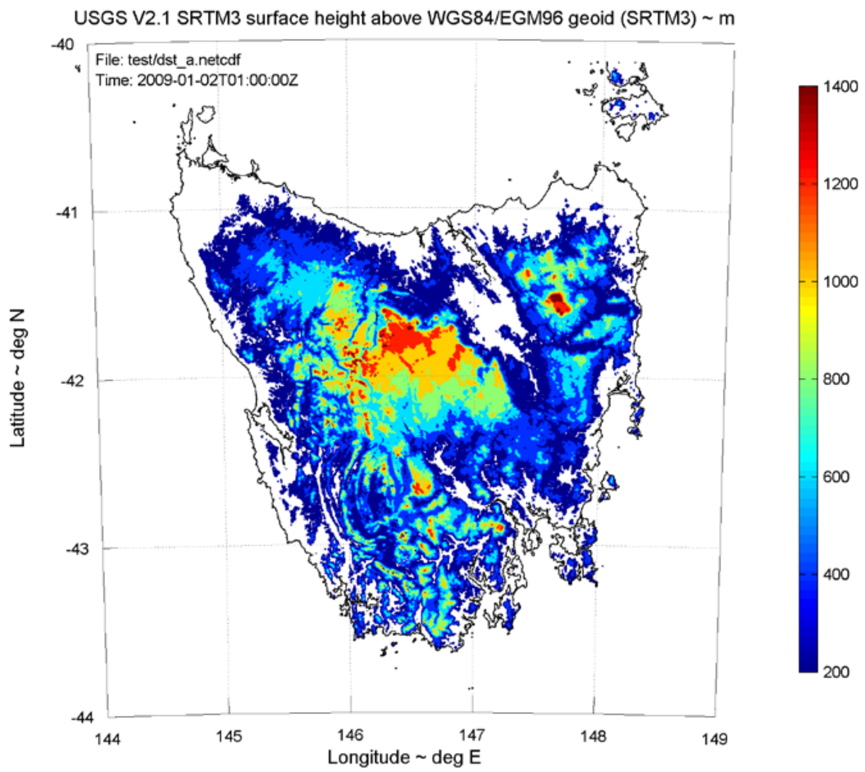
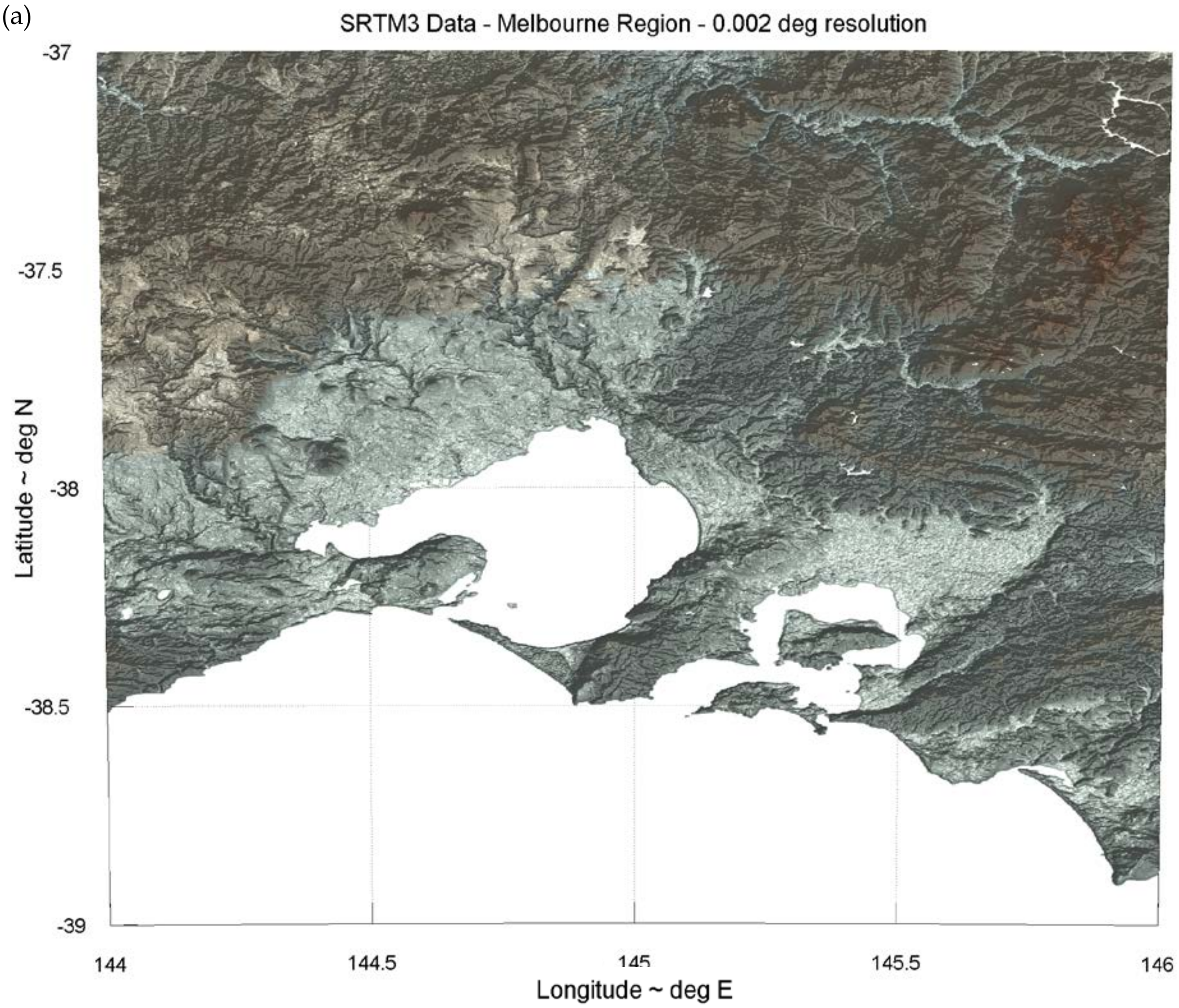


Figure 4 Terrain-elevation data for Tasmania: (a) the relatively low-resolution data provided by default by the DEDS and used in mesoscale weather modelling and (b) high-resolution SRTM3 data also available from the DEDS

(a)



(b)

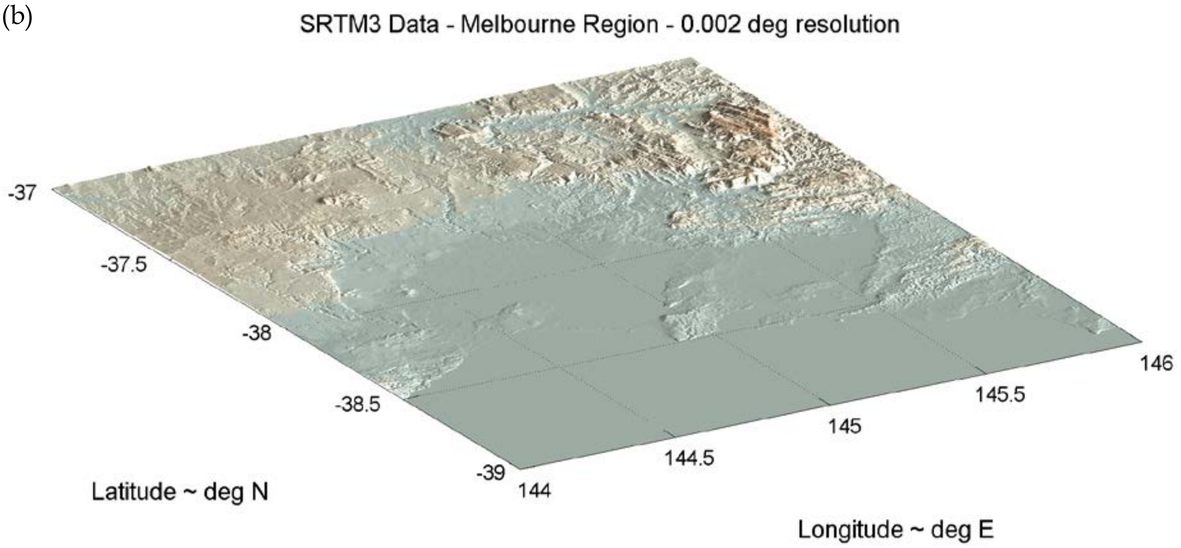


Figure 5 SRTM3 terrain-elevation data output by the DEDS for the region around Melbourne: (a) a plan view of the region and (b) a rendering of its topography

Elevation Data (DTED) format [35, 36]. Existing tools may be used to convert SRTM3 geoTIFF-formatted data to DTED format [37]. Upon request, the DEDS converts SRTM3 data to a version of the DTED format, DTED-1, which has a grid resolution of 3 arcsec.

2.2.2 Mesoscale Meteorological Data

2.2.2.1 Raw Data

Synoptic-scale weather data output by the Global Forecast Service (GFS) model [38] is freely provided by the US National Oceanic and Atmospheric Administration (NOAA) [39], in association with a number of other organisations. Each dataset includes then-current global weather conditions (a "now-cast") created by the assimilation of data from thousands of sources, including satellites, local weather monitoring stations, and pilot reports. The results are on a three-dimensional (3D) grid with a latitudinal and longitudinal spacing of 0.3° or 0.6° (35 or 70 km), depending on region, over the entire globe and approximately sixty vertically spaced grid points. Examples of graphical representations created from the GFS output are displayed in Figure 6.

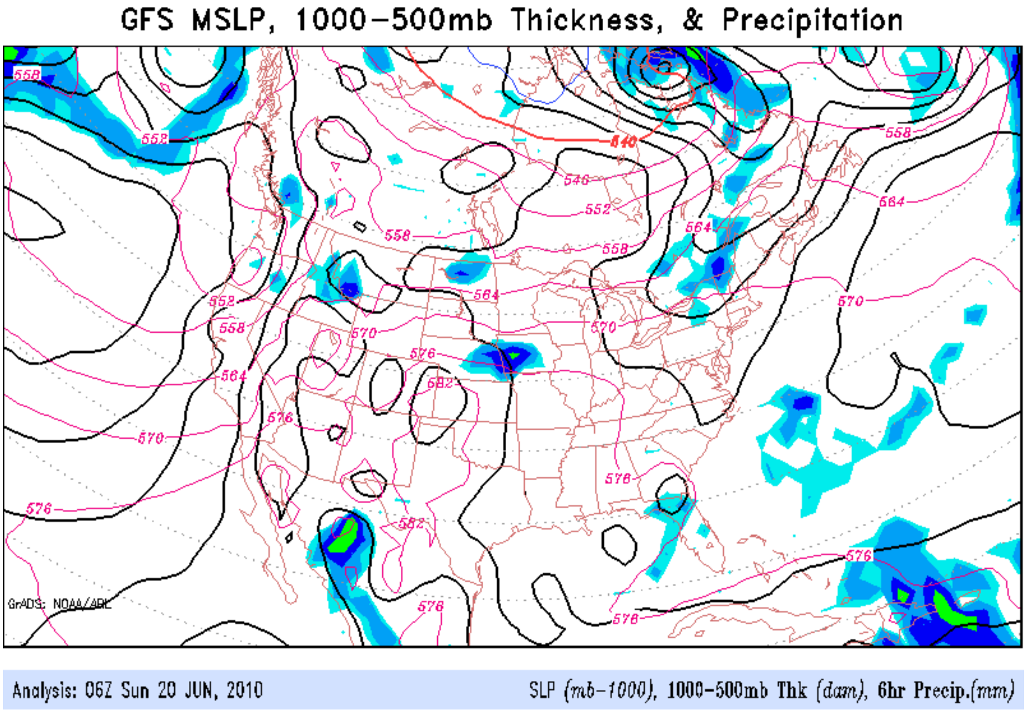
NOAA releases now-casts for the current 24-hr period via several public servers [40] in GRIdded Binary (GRIB) format, a file format commonly used for weather observations [41]. The GFS data is released at 0000, 0600, 1200, and 1800 hr universal time coordinates (UTC) and is accompanied by three-hourly forecasts covering a ten-day period following each now-cast. That information is used by weather-forecasting services around the world to produce daily forecasts [42, 43]. The data is also archived by NOAA for six months and made available free of charge to the public [44].

At present, the DEDS automatically downloads the GFS now-cast valid at 1800 UTC (0400 Australian Eastern Standard Time) and forecasts covering the following 24-hr period. This comprises 450 MB of data, which is stored locally on the server. Global weather records from November 2006 onwards have been downloaded and archived by DSTO; however, the GFS data archived on the DEDS for dates before June 2008 is incomplete and, in some regions, may be adequate only for hindcasting over a 12-hr period of each day (0700–1900 UTC), rather than the entire day. Data to permit 24-hr hindcasts has been downloaded for the period after June 2008 and will continue to be downloaded henceforth.

Because the DEDS is used as a research tool and purely for historical meteorological analysis, uninterrupted, high-bandwidth internet access is not required to keep its GFS archive current within each 24-hr period. The software employs logic to repeat requests for GFS data from the NOAA's public servers if the first attempt is unsuccessful; and administrators and users can monitor the archive to ensure that raw data is accumulated within the six-month window during which it is easily accessible from NOAA.

Mesoscale atmospheric models, such as the one used by the DEDS, are initialised with spatial and temporal boundary conditions from synoptic-scale (low-resolution) data and account for local effects (*e.g.*, terrain and land use) through the use of parameterised physics models [45, 46]. This is referred to as "down-scaling". Data describing geographic regions

(a)



(b)

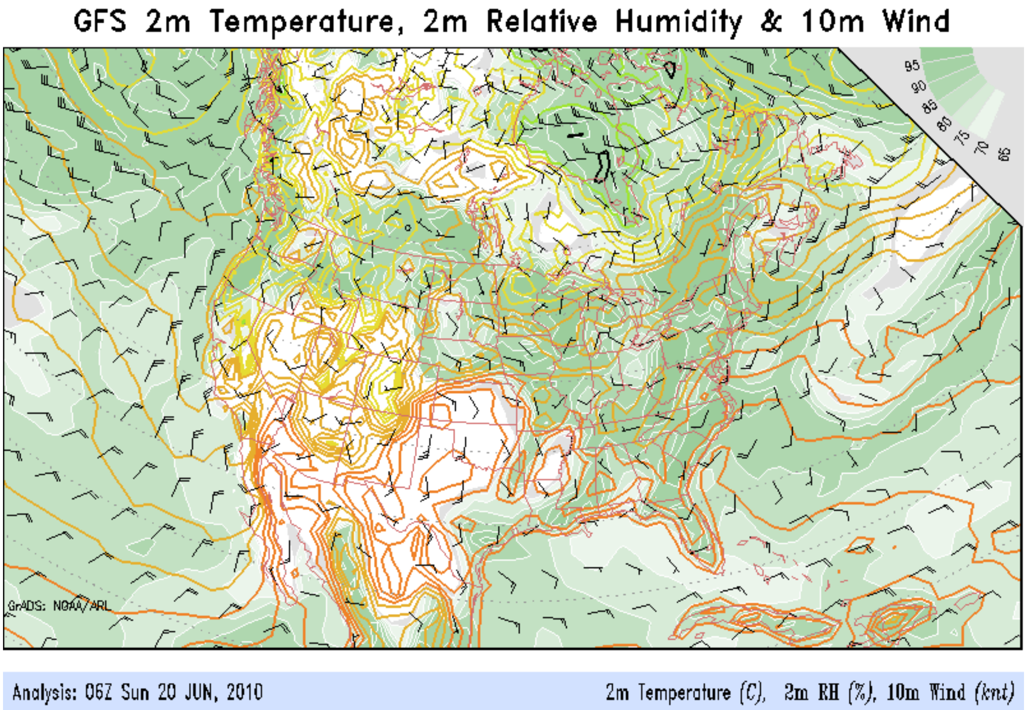


Figure 6 GFS now-cast data for 0600 hr Zulu on 20 June 2010 over the US. (a) The mean sea level pressure (MSLP), thickness of the atmospheric layer in which the ambient pressure falls from 1000 bar (the surface) to 500 mbar, and rate of precipitation. (b) The ambient temperature and relative humidity at 2 m above ground level (AGL) and wind speed and direction at 10 m AGL. Available at: http://ready.arl.noaa.gov/READY_animations.php; produced by NOAA, and reprinted as an un-copyrighted work of the US Government.

that is needed for mesoscale weather modelling is stored on the server. The data, which includes information about annual soil temperatures, top-layer soil type, land-use category, monthly green fraction, monthly surface albedo, and coarse topography height [47, 48], is provided by NOAA on a grid with a spatial resolution of roughly 30 arcsec latitudinally and longitudinally, which equates to 0.00833° (or 917 m at the equator [28]).

2.2.2.2 Mathematical Models

The Weather Research and Forecasting (WRF) model, Version 2.2 [49-51], developed by NOAA, the US National Center for Atmospheric Research (NCAR) [52], and more than one-hundred and fifty universities and other organisations worldwide, is used by the DEDS for regional (or mesoscale) atmospheric modelling. The computations are typically performed in response to a user's selection of 'Mesoscale Weather' as the data-retrieval type, as illustrated in Figures 2 and 3.

The WRF model requires the use of the WRF Standard Initialisation (WRFSI), a collection of tools that includes a GUI for data generation, GRIB-data pre-processing routines, and a post-processing routine. The DEDS also uses the Regional Atmospheric Soaring Prediction (RASP) software package [53], which bundles and executes WRFSI and WRF. The flow of inputs and outputs and the relationship between WRF and RASP are illustrated in Figure 7. The GFS data described above is stored in the "GFS archive" shown at the top of Figure 7, whereas the "Reanalysis archive" is intended to store global weather data published by NOAA from the period before GFS became its data-format standard. Currently, the DEDS holds none of the older data; however, its acquisition could be undertaken by future users (§4.1.2).

In its open-source version, RASP permits requests for regional weather forecasts. It collects the necessary geographical data and retrieves GFS data from one of the NOAA servers, which may take up to three hours to become available. RASP then runs the WRFSI tools in an appropriate order, followed by the WRF model. NCAR Command Language (NCL) [54] and image-format conversion routines are used to produce images of current and forecast weather conditions in the region of interest.

In the context of the requirements for the DEDS, several difficulties exist with the unaltered version of RASP. The delay in producing results (based on the need for GFS data that is current when the request is made) is unacceptable, and only one instance of RASP may be run on a single computer, eliminating the possibility of parallel computing of, *e.g.*, multiple days for a given region. In addition, faults (*e.g.*, missing GFS data) are poorly managed, and there is minimal warning or feedback when failures occur. Furthermore, the use of RASP for hindcasts is non-standard and thus prone to faults.

To overcome these limitations, the DEDS relies on a customised version of the RASP interface created by DSTO researchers. It permits regions for mesoscale weather modelling to be manually generated by the user through the DEDS GUI or requested through the API. As described above, GFS data is archived in a local data store; and RASP is operated in a hindcasting mode in which the two GFS now-casts that bracket the time requested for modelling are input to WRF as temporal boundary conditions. A key feature of the

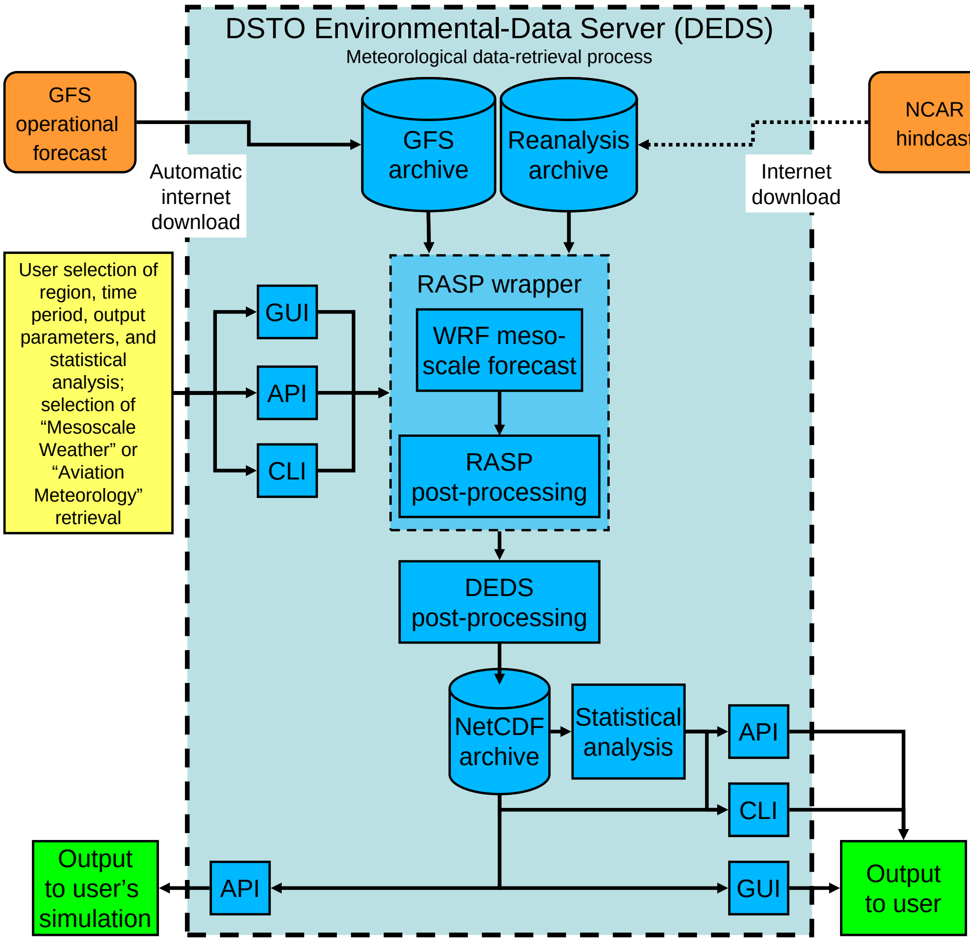


Figure 7 Flow chart illustrating DEDS processes and interactions with data sources, user inputs, and outputs for a meteorological data-retrieval request

customised version of RASP is that the Network Common Data Format (NetCDF) [55] files output by the WRF model are retained as the authoritative modelling results for the simulation period.

The output of WRF, described in more detail in §2.2.2.3, includes a standard set of meteorological parameters at user-defined latitudinal and longitudinal resolutions, typically 1–20 km; though the DEDS GUI permits users to choose a grid size of 6 km × 6 km or 12 km × 12 km only. The vertical resolution is also variable, with output being generated over (typically) forty to sixty pressure levels that may be exponentially or linearly spaced, as selected by the user. By default, the DEDS performs mesoscale weather modelling and generates results at fifty-two (approximately) exponentially spaced pressure levels.

The variation of the geometric height of the vertical levels with index number is illustrated in Figure 8 for a case in which the terrain height is at the mean sea level (MSL). The corresponding geopotential height of each point is also plotted. The geopotential height is slightly lower than the geometric height, though the difference is imperceptible in Figure 8. For

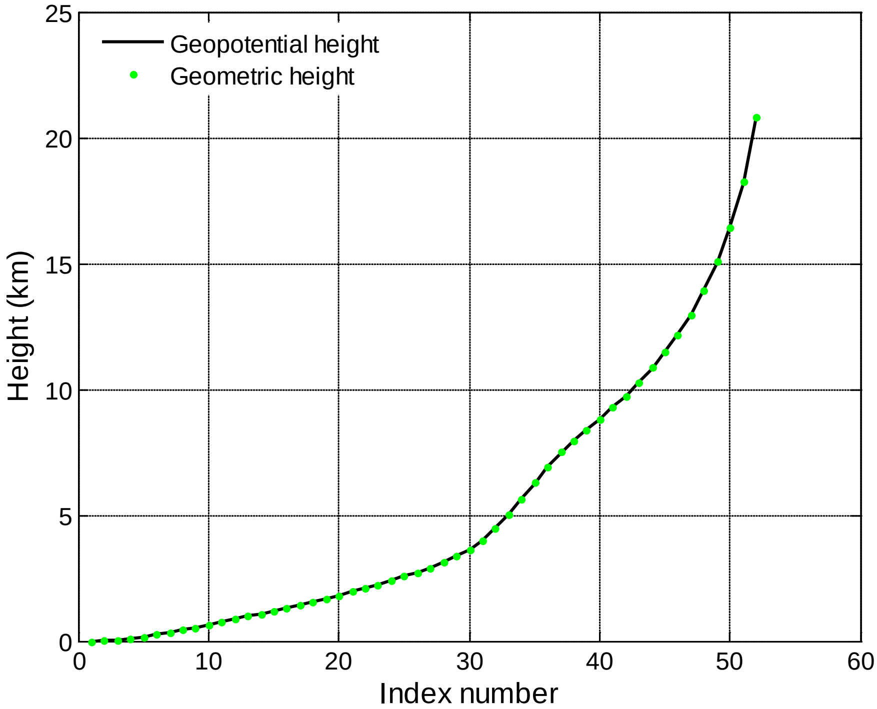


Figure 8 Variation of height with vertical index number in the grids used to perform mesoscale meteorological computations

locations where the terrain is above MSL, the vertical levels are scaled between the terrain height and the maximum height shown in Figure 8.

By default, the DEDS executes the WRF model with a 2-min time step and produces hourly outputs, though both settings are configurable via the API or CLI. Adjusting the spatial and temporal resolution of the model through the settings of the grid spacing and computational time step permits the user to find a good compromise between data-storage space, run time, and numerical accuracy for a given region. A user may also desire more frequent output; and this, too, may be requested by the user via the API or CLI.

A user may also select 'Aviation Meteorology', a data-processing type that causes the DEDS to compute additional quantities specific to aviation-related analyses and aircraft flight simulations, including: ambient static pressure and absolute temperature; relative humidity; specific-heat ratio; ambient speed of sound; specific gas constant; dewpoint and frost-point temperatures; freezing-level geopotential height; spatial gradients of wind velocity; and dynamic viscosity.

2.2.2.3 Output

After RASP executes WRF in response to a user request for 'Mesoscale Weather' data, it extracts information useful to glider pilots from the WRF output files by use of NetCDF Command Language (NCL) tools [54]. The DEDS post-processes the resulting files and appends the results to the RASP output to produce one-hundred and sixty-eight scalars,

vectors, and 2D and 3D matrices that describe the atmosphere and terrain in the region for which weather data was requested. The results are available at geometric heights from the ground surface to the top of the atmospheric-boundary layer (ABL) and include several temperature- and pressure-related variables, cloud density, and wind and vertical air-mass speeds. Tables of the variables provided by the DEDS in its NetCDF output, along with a brief description of each, are given in Appendix A. Table A.1 lists the variables in the standard output, generated when 'Mesoscale Weather' is selected by the user; and Table A.2 lists those provided when 'Aviation Meteorology' is chosen.

Figures 9–11 show examples of the imagery generated by the DEDS in Portable Network Graphics (PNG) format as part of a data-processing and -retrieval request for mesoscale weather modelling. A 1000-km × 1000-km region, centred at 34° N, 112.5° W (near Phoenix, Arizona, in the Southwestern US) and bounded by a red, dashed line in Figure 9(a), was selected through the DEDS GUI; and mesoscale weather modelling was performed. Figure 9(b) shows contours of terrain height, the boundary of the computational region (the box drawn with a dashed white line, which encompasses the user-selected region), and the political borders in the area. Dashed black lines indicate the shorelines, which along with the other features in Figure 9(b) were created by the plotting routines in RASP, which utilise a Lambert conformal conic projection [56].

Several of the basic weather parameters output by the mesoscale hindcast are displayed in Figures 10 and 11. The images show the hindcast conditions valid for 1200 hr local standard time (LST) on 1 December 2007. As these images illustrate, the day was relatively cool and

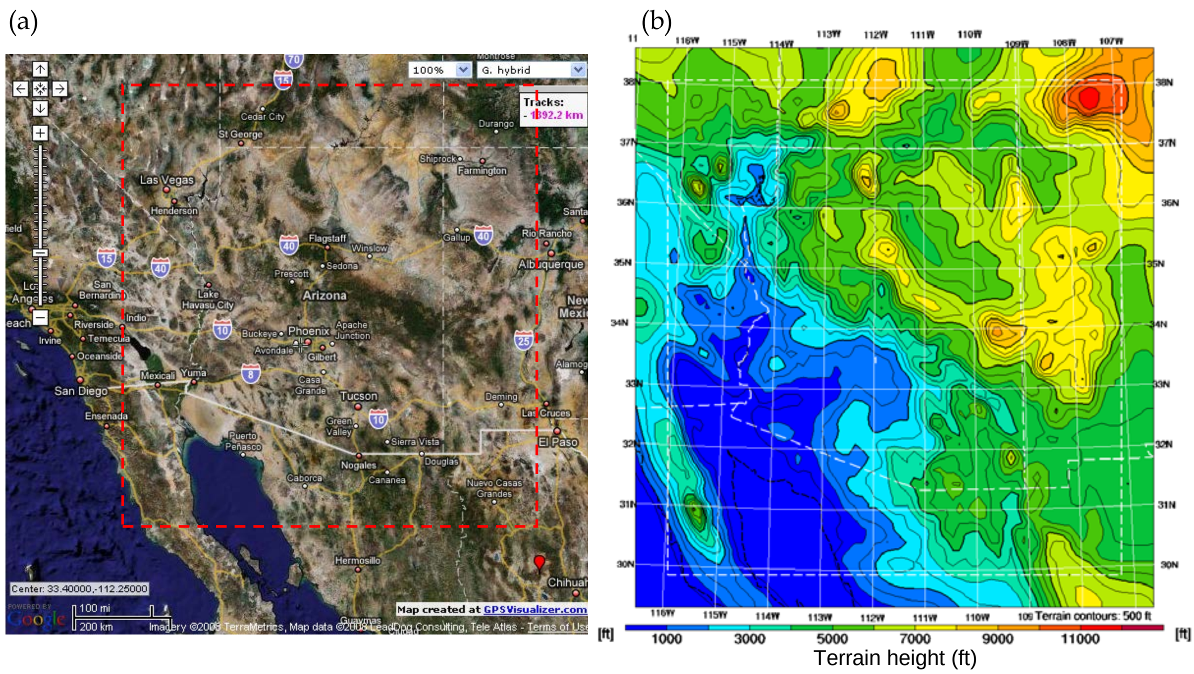


Figure 9   Maps of a 1000-km × 1000-km area approximately centred on Phoenix, Arizona, the region over which a hindcast was generated by the DEDS, produced by (a) Google Maps and (b) the DEDS

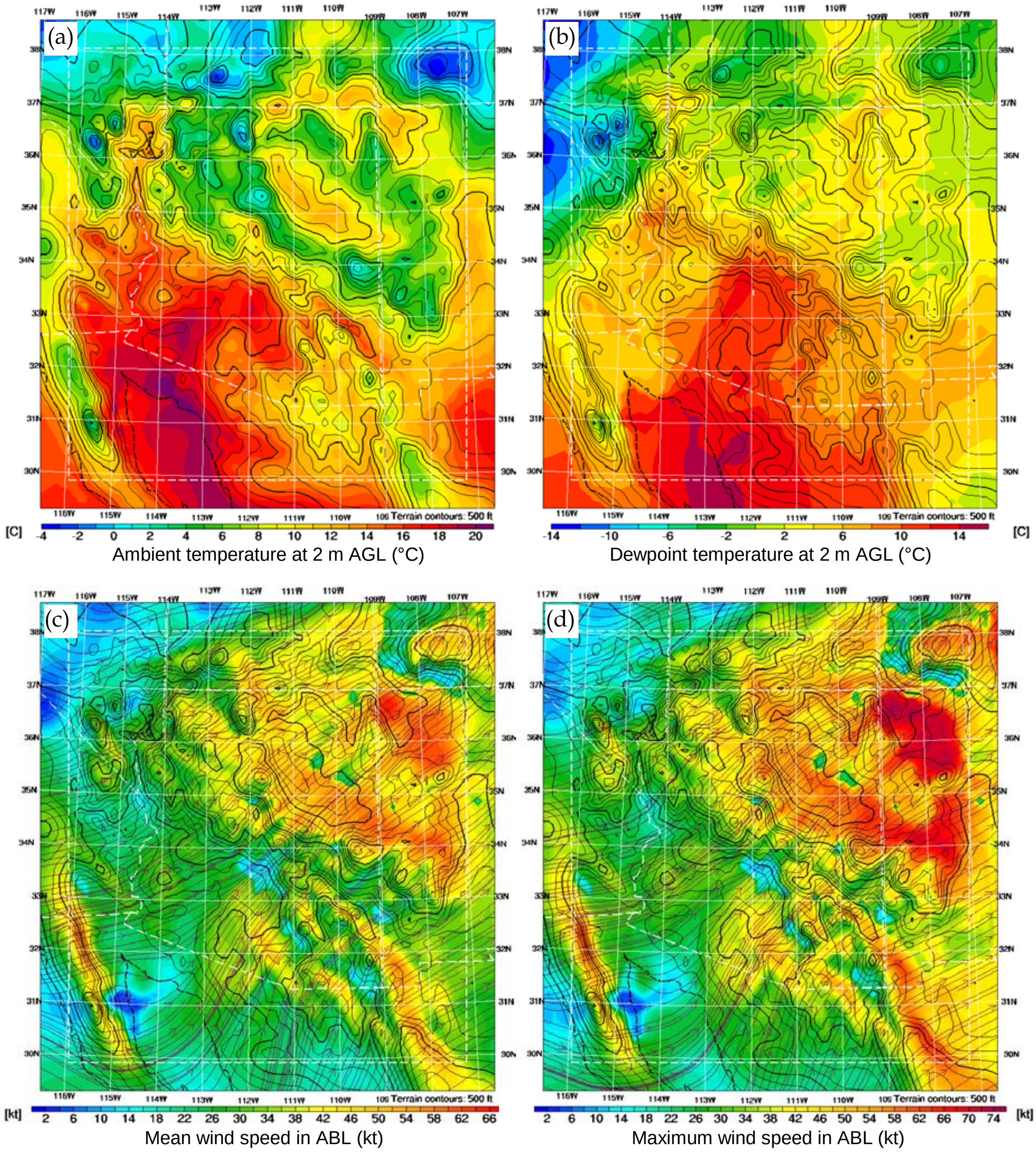


Figure 10 (a) Ambient and (b) dewpoint temperatures at 2 m AGL, and (c) mean and (d) maximum horizontal wind speeds in the ABL hindcast by the DEDS for 1200 hr LST on 1 December 2007 in the region of Arizona

overcast for the Arizona region. The parameter shown in Figure 11(a), the convective available potential energy (CAPE), is a measure of atmospheric instability and an indicator of the likelihood of storms; indeed, rain occurred at 1200 hr and during the remainder of the day. The sample of data provided here is but a small portion of that generated by the DEDS for 1 December 2007 and an even smaller portion of that used in the analysis of the flyability of a small UAS in the region of Arizona described in §3. The NetCDF files for this region,

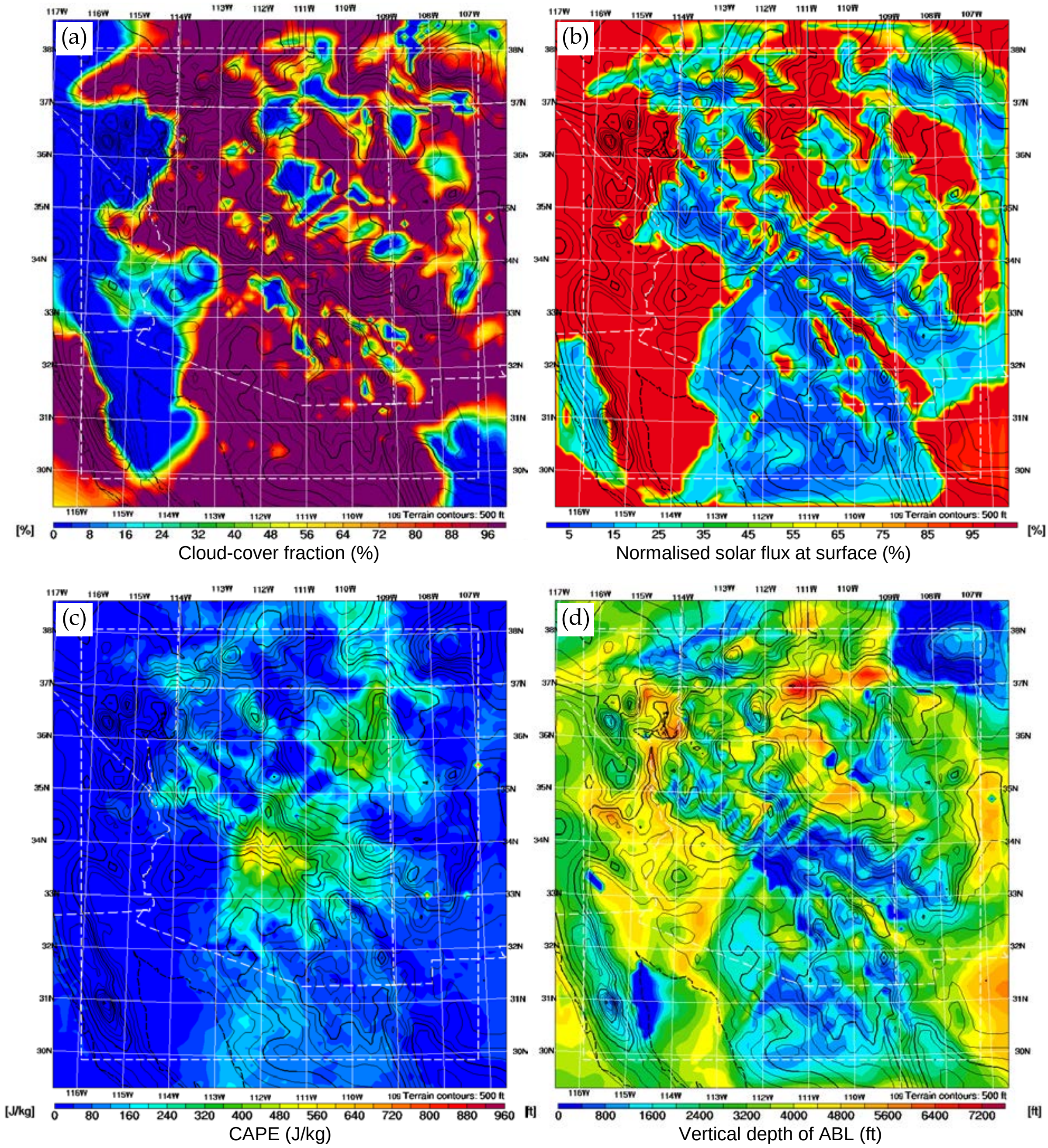


Figure 11 (a) Cloud-cover fraction, (b) normalised surface solar flux, (c) CAPE, and (d) vertical depth of the ABL hindcast by the DEDS for 1200 hr LST on 1 December 2007 in the region of Arizona

which contain a complete set of atmospheric parameters at the requested time, including those shown here, are 34 MB in size; and one was generated for every hour of the hindcast. To analyse a three-and-one-half-year period, as was done to create the results shown in §3, a database comprising more than 1 TB of weather data for the Arizona region was required.

As described in §2.2.2.3, DEDS users may elect only to obtain 'Mesoscale Weather' data; or they may make an 'Aviation Meteorology' request, to compute an additional thirty variables commonly used in aviation analyses, *i.a.* If a 'Mesoscale Weather' request has already been made for a given region and time, the DEDS responds to an 'Aviation Meteorology' request by simply creating a new set of hourly NetCDF files, providing the additional variables; whereas requesting an 'Aviation Meteorology' retrieval first causes the DEDS software to perform the necessary mesoscale weather modelling and to generate its output before it computes the additional variables and appends them to the NetCDF files. A table of the variables provided by an 'Aviation Meteorology' request is given in Appendix A.

2.2.2.4 Model Validation and Updates

The GFS and WRF models are subject to continuous scrutiny, verification, and improvement by a large community of users worldwide [57, 58] and thus have been relied upon in the development of the DEDS without supplementary V&V. Updates to the GFS, which is under continuous development, and changes to the format of its output may be incorporated into the DEDS with minimal changes. Significant changes to WRF, which occur every two to three years, would be more difficult to incorporate, because of the use of RASP by the DEDS; however, as the DEDS software is modular, it would be possible to entirely replace RASP with customised code if such a transition were necessary. At present, a version of WRF that is several years old [51], but only minimally different to the current version in its mesoscale-hindcasting capabilities, is employed by RASP and the DEDS. As with all IT systems, there is a need to balance the desire to update software to the latest versions with the need to ensure stability of the integrated system.

2.2.3 Building Geometry

Geo-referenced building-geometry data has been acquired commercially for the central business districts (CBDs) of Australian capital cities [59]. The data is stored in a geo-referenced vector-data format, Environmental Systems Research Institute (ESRI) Type 15 Shapefiles [60], from which building geometries are extracted as 3D polygons. It may be output in that or other formats suitable for visualisation and scientific modelling. Examples of renderings of building-geometry data output by the DEDS are provided in Figure 12.

Initial tests on the building data revealed a number of potential sources of error. In particular, the data was reviewed to ensure that any height offsets due to terrain were removed. Further work is required to make estimates of the final resolution and horizontal and vertical errors for the dataset.

2.2.4 Population Density

Population information for Australia is collected by the Australian Bureau of Statistics (ABS) [61], which conducts a national Census of Population and Households every five years. Some versions of the census data, providing the population by geographical area, are freely available from the ABS. The data used to create the DEDS population-density model

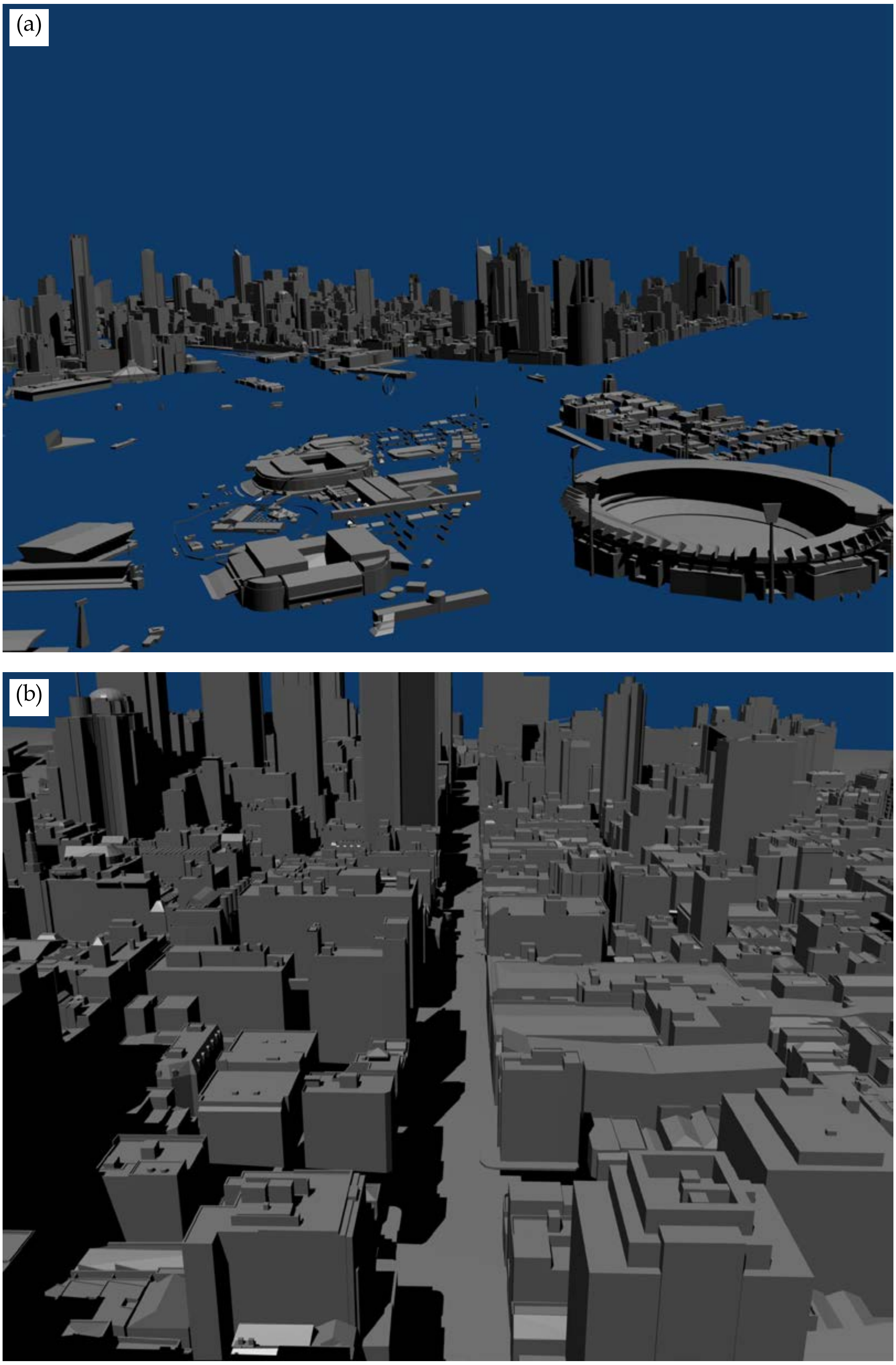


Figure 12 Renderings of building-geometry data for Melbourne viewed (a) from the Southeast, with the Melbourne Cricket Ground prominent in the foreground, and (b) from the West along Bourke Street

was derived directly from the 'Estimated Resident Population, Local Government Areas' data from the 2006 census [62].

In order to re-sample ABS population data on a regular grid, it was necessary to have a description of the boundaries of the sampling regions and to assume that, within each sampling region, a uniform population distribution exists. The regions used for this purpose were based on the 'Australian Standard Geographical Classification Digital Boundaries for Local Government Areas', published by the ABS in 2007 [63] and defined in a spherical projection in units of degrees latitude and longitude, known as the Geocentric Datum of Australia 1994 (GDA94) [64].

As shown in Figure 13, the regions in which population-density data is available from the DEDS vary greatly in size. Thus, the population and population-density estimates are accurate in smaller, heavily populated local-government areas, such as those in Australian capital

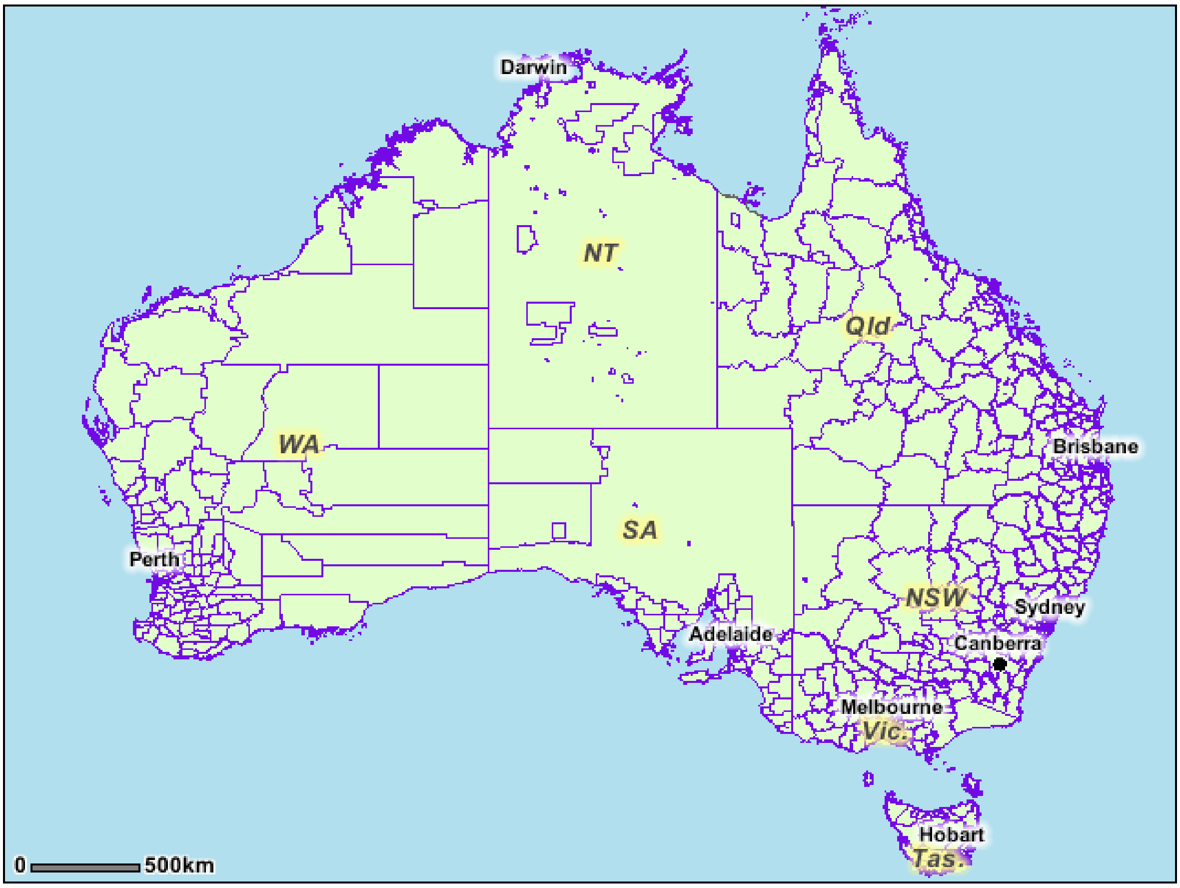


Figure 13 Local government boundaries used as sampling regions for population-density data by the DEDS, available at [http://www.censusdata.abs.gov.au/ABSNavigation/prenav/LocationMap?newgeography=Local+Government+Area&collection=Census&period=20&areacode=&geography=&method=&productlabel=&producttype=MapStats&topic=&n vmapdisplayed=true&javascript=true&breadcrumb=PL&topholder=0&leftholder=0&cu entaction=103&action=103&textversion=false&subaction=0]

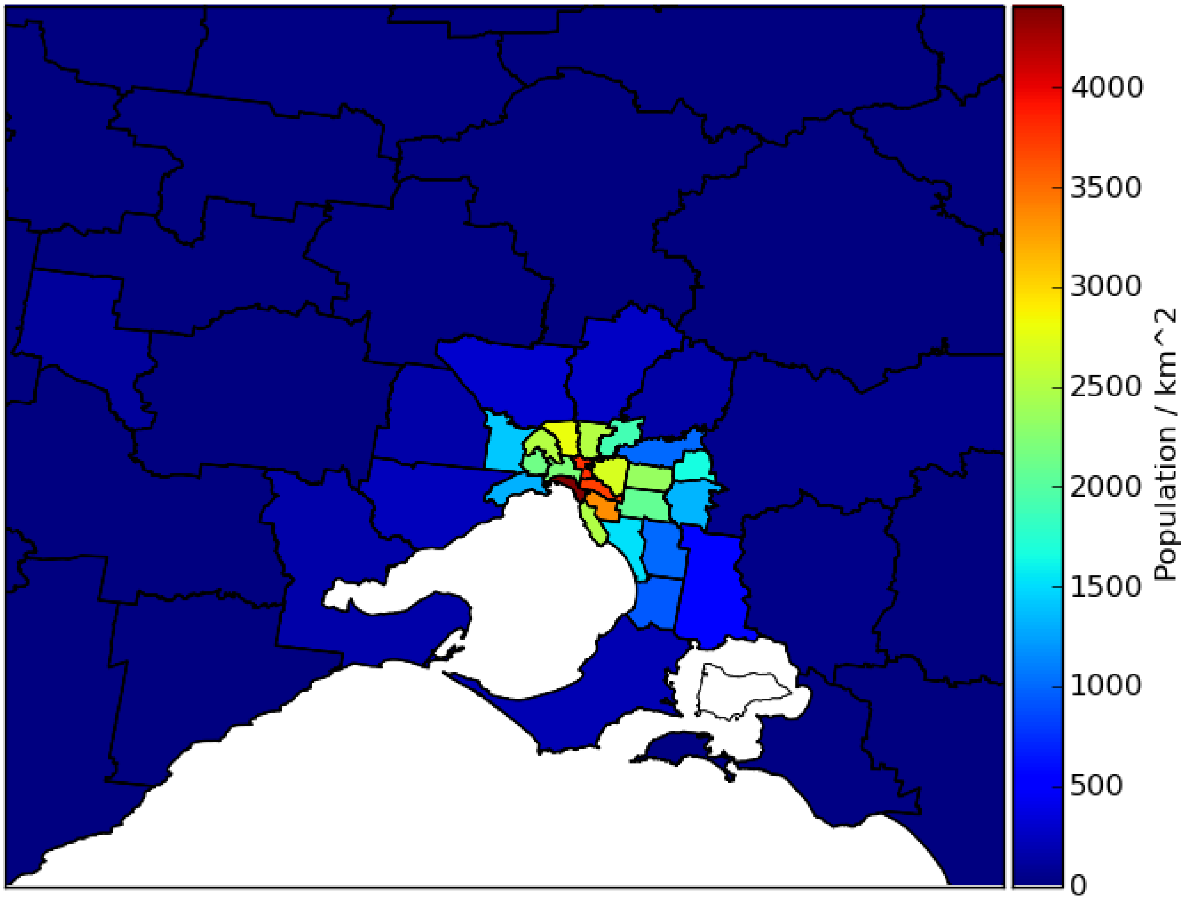


Figure 14 Population-density data available from the DEDS for the Melbourne region

cities, than in sparsely populated regions. A sample of the population-density data available from the DEDS is provided in Figure 14, which shows the Melbourne region.

The accuracy of the DEDS population-density model is influenced by several factors, most significantly the accuracy of the raw population data from the ABS. Since 2007, the ABS has maintained documentation on the quality of census data, noting the inherent inaccuracies involved in population measures [65]. The sampling method used to place the data on a regular grid is another source of error. Furthermore, as the currency of the population measurements used by the DEDS declines, the validity of the population-density model decreases. Approaches to improving the accuracy and currency of the data are discussed in §4.

2.3 Data Management

Two types of data are stored on the DEDS server, the first of which is the source data required as input to data-retrieval requests, including the terrain-height, historical GFS weather, building-geometry, and population-density data described in §2.2. The second type comprises archived results of data processing. This includes weather hindcasts and copies of processed

terrain and building data in several formats. This approach eliminates unnecessary re-processing and minimises delays for on-going modelling operations.

Internally, the DEDS employs a scheduling system to ensure that all dependencies are met prior to performing analyses or delivering results. For example, before an attempt is made to run RASP, the necessary GFS data and other inputs are identified and their availability verified. This design aids in the management of exceptions and missing data.

Whilst external standard data-management protocols are used when the DEDS is accessed from the web GUI or CLI, access through the API allows the user significantly more control over the use of network bandwidth and caching of results.

2.4 System Administration and Hardware Requirements

2.4.1 New Installations

A number of software packages comprise the DEDS. The latest copies of these packages are available upon request, and access to the development branch is available via a source-control tool, 'git' [66]. The DEDS was designed to be run on a Linux-based computer with a kernel supporting virtualisation through the OpenVZ system [67, 68]. New site installations of the DEDS may be performed from source code by use of standard Linux tools, as described in the DEDS Installation Manual [4].

2.4.2 Interoperability

As described in §2.1, the DEDS enables access via a variety of methods, including a web interface and a custom API, though which extensions running on the DEDS may access the server. Access to the DEDS API in programming languages other than C and C++ can be achieved through the use of a software-development tool called the Simplified Wrapper and Interface Generator (SWIG) [69, 70]. The use of SWIG to generate the APIs ensures that the usage of the system is consistent and affords programmers flexibility in their choice of language. Currently, Perl bindings are available for the API; and additional languages such as Lisp, Lua, Java, and Python could be incorporated in future releases.

Depending on future user requirements, standardised programming interfaces could be incorporated into the DEDS to permit the server software to be used directly by simulations following the Distributed Interactive Simulation (DIS) and High Level Architecture (HLA) standards [71]. A SEDRIS-compliant interface [72] could also be incorporated, to standardise the output of the DEDS for use in simulations utilising environmental-modelling data.

2.4.3 Scalability

The DEDS achieves scalability in two ways. The first is by allowing any computer with appropriate software to participate in a DEDS cluster. This means that the system may effectively encompass a large number of physical computers. Secondly, each of the computers in a DEDS cluster may run multiple jobs simultaneously. Whilst this is facilitated in part by a

kernel that supports multi-tasking, neither RASP nor WRF was designed for such a possibility. Thus it is only possible to run one instance of each on a computer at a time. The DEDS, however, achieves a high degree of parallelism by running all jobs in separate, virtual computers (*i.e.*, OpenVZ virtual machines [67, 68]).

A limitation of this strategy is that some initial administration is required to share both internal and computed environmental datasets across the entire DEDS cluster. Currently this is achieved by providing both high-speed internal hard drives and bulk data storage. The DEDS installation manual [4] documents the steps necessary to share storage amongst all computers in a cluster. The current site-installation of the DEDS includes 28 TB of storage, which is deemed sufficient for archived and generated data for the foreseeable future.

The design philosophy of the DEDS is to enable users to process very large amounts of environmental data remotely. This approach means that large computational problems may be distributed across a cluster, and only the final results of the processing need to be transmitted to an end-user. The advantage of this design is that it reduces network traffic and enables efficient sharing of computational resources. In cases where finer control over processing of results is required, the DEDS API may be utilised.

2.5 Intellectual Property (IP) and Licensing

2.5.1 Access to Third-Party IP

Open-source and other freely distributed source software was used in all parts of the DEDS; thus, licensing has not been required for the server design, software, or programming interfaces. The software written in the project is an asset of the Commonwealth.

Similarly, the datasets for population density, meteorological modelling, and terrain height have been obtained from sources that freely distribute the data, either strictly for scientific purposes or for any purpose. In contrast, the building-geometry data available from the DEDS is licensed to DSTO commercially [59]; usage outside DSTO would require additional license(s).

2.5.2 On-Going Support

Currently the DEDS is supported under several DSTO research tasks and is accessible via the DSTO network. It is administered by Maritime Division and Aerospace Division personnel, and the site-installation is physically housed at Fishermans Bend. The authors of this report utilise the DEDS software for research purposes and do not offer on-going support to other users.

2.5.3 Certification and Licensing of the DEDS

In the event that operational forecasting applications were pursued with the DEDS software, certification for installation on other Defence networks would be required. This process would likely take considerable time and effort; however, it was not required for the development

project, nor was it required for the research applications described herein. Thus, certification of the software has not been undertaken.

If the DEDS software were to be distributed beyond Defence, DSTO's Business and Commercialisation Office would need to be consulted to develop a licensing scheme for the software and to manage Defence's liability and intellectual-property rights under any third-party use. No plans exist to do this.

2.6 Confidence Building

2.6.1 Verification, Validation, and Accreditation

Validation and verification of the underlying data sources and models utilised by the DEDS, *e.g.*, the GFS and SRTM data and the WRF model, are performed on an on-going basis by a great number of academic and governmental research institutions [57, 58]. Therefore, the developers of the DEDS performed V&V to give confidence that the source data is accurately represented when transformations or other models are applied by the DEDS software. Basic checking and comparisons of model outputs against observations and other data sources were adequate to yield trust in the data produced by the software.

The DEDS software was designed for historical analyses. A forecasting capability has not been implemented, nor is one recommended by the authors. However, if the DEDS were ever to be adapted for weather forecasting, the BoM or other subject-matter experts could be enlisted to provide guidance on the use of its meteorological models and data. Future users of the DEDS may also wish to consult the BoM about techniques for statistical analyses of weather data, depending upon the applications they pursue.

2.6.2 Informal Approaches to Trust

The development of the DEDS infrastructure and interfaces followed an incremental strategy to allow DSTO end-users to be involved in feature and interface design and to gain experience with the system. This occurred over the course of several years, with the last being funding by ADSO.

The applications described in §1.4 have exposed the DEDS to real-world testing and demonstrated some of the benefits it offers Defence. In addition, other research studies relying on the system have been published [19, 20]; and several projects are on-going [2, 73-75]. These studies have shown that that the DEDS is fit-for-purpose for the applications for which it was designed. Future users will, however, need to make similar assessments about its suitability for any applications they may wish to pursue.

3. Sample Application: Tactical UAS Performance

In this section, a simple weather-based analysis of the performance of a small tactical UAS is described. It demonstrates one type of statistical investigation that may be conducted by use of the weather-modelling features of the DEDS.

3.1 Performance Analysis

Weather and climate impact the operations of UAS because their performance is contingent on the availability of the air vehicle to fly in current atmospheric conditions. Weather conditions may also affect the ability of sensors to provide useable ISR data. Amongst the most basic constraints on UAS flight availability or "flyability" are the need for the aircraft to make headway in prevailing winds and the need for its operator to maintain control. A variety of flyability measures could be considered to examine the potential utility of a given platform in a given region. For example, in the simplest case, when (and where) the mean wind speed is expected to be greater than 70% of the cruising speed of the UAS, the aircraft may be considered to be un-flyable and thus unavailable to conduct a mission.

For a given day, a mesoscale weather forecast, or in this case a hindcast of a past day, may be used to assess the fraction of time that the UAS would be flyable as a function of location (latitude, longitude, and altitude) within the region. Flyability values may be assigned to each grid location within the region at a given time, with a value of unity meaning that the aircraft is flyable according to the established criteria and a value of zero indicating that the aircraft is unflyable. Averaging the flyability values over the entire region yields the (spatial-) mean flyability in the region at that time; and averaging over a given period of time at each grid location yields the (temporal-) mean flyability of the UAS as a function of location.

3.2 Historical Conditions in a Given Region

The US State of Arizona has been chosen as a representative region in which one might wish to operate a tactical UAS for ISR missions (*e.g.*, border patrol or wildfire monitoring); and the DEDS has been utilised to create a statistical view of atmospheric conditions in the region shown in Figure 9. The Arizona region was selected through the DEDS GUI; and mesoscale weather modelling was performed for each day of the period from 1 January 2007 to 31 May 2010.

The weather modelling results output by the DEDS for each hour of each day include the maximum wind speed in the vertical air column through the ABL at each latitudinal and longitudinal location (horizontal grid point) in the region. A Perl script was up-loaded through the DEDS API to determine the distribution of the output maximum-wind-speed values at each grid point during Winter (Dec–Feb), Spring (Mar–May), Summer (Jun–Aug), and Autumn (Sep–Nov); and the limiting wind speed below which 90% of the values occurred was evaluated for each season. This value, termed the 90% confidence level (CFL) of the maximum wind speed, is displayed in Figure 15 on a seasonal basis.

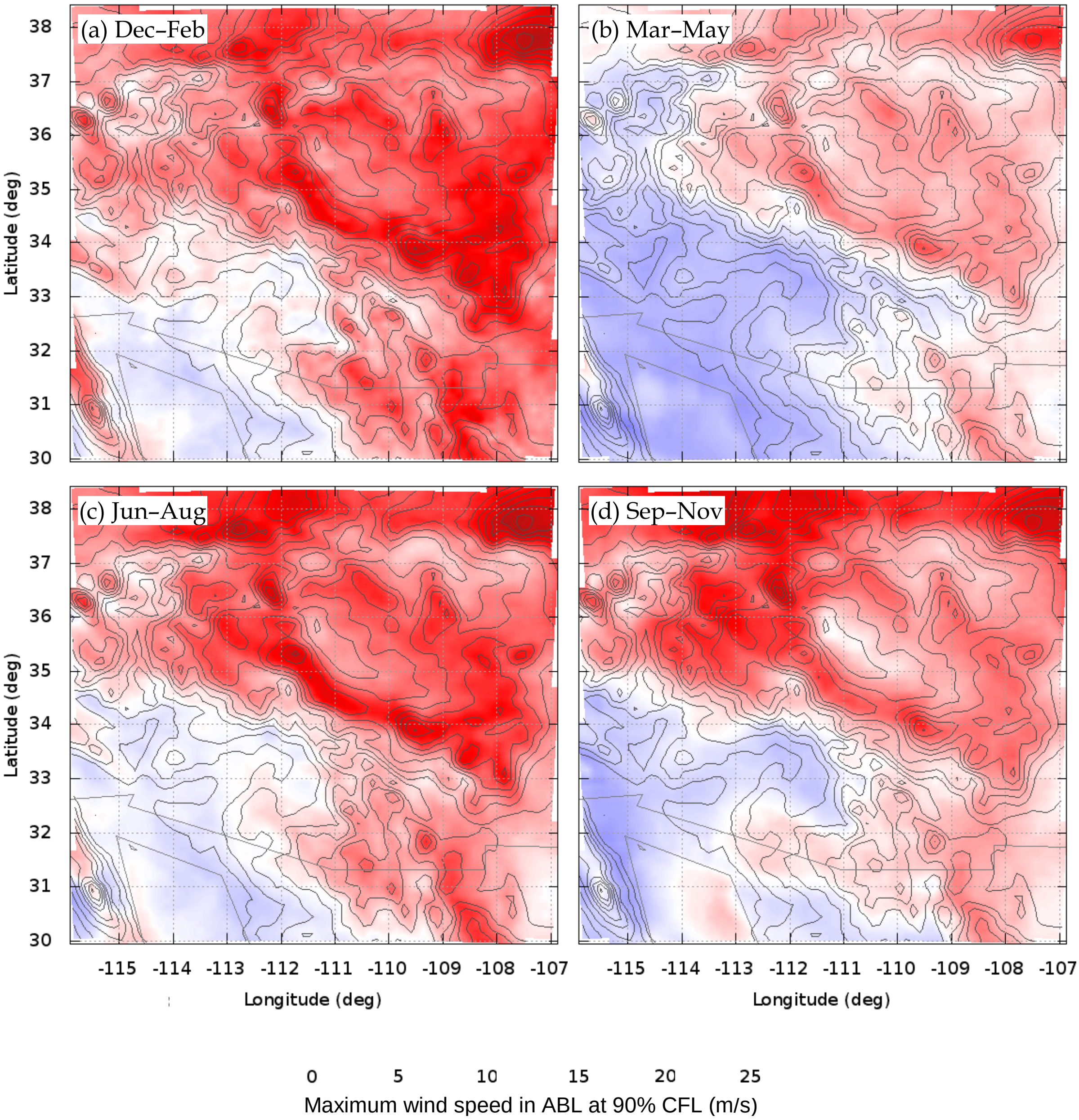


Figure 15 90%-CFL maximum wind speed evaluated on a seasonal basis from hindcasts in the period of 1 January 2007 to 31 May 2010 by the DEDS for the region of Arizona

3.3 Statistical Analysis of UAS Flyability

The weather data used to determine the 90%-CFL maximum wind speed over the region of Arizona was also used to evaluate the regional flyability of a small, tactical UAS, several examples of which are shown in Figure 16. An aircraft with a best-range (cruising) airspeed of 20 m/s, a value typical of the aircraft in Figure 16, was considered in the analysis; and the maximum wind speed at which the aircraft would be flyable was taken to be 70% of this value, or 14 m/s.

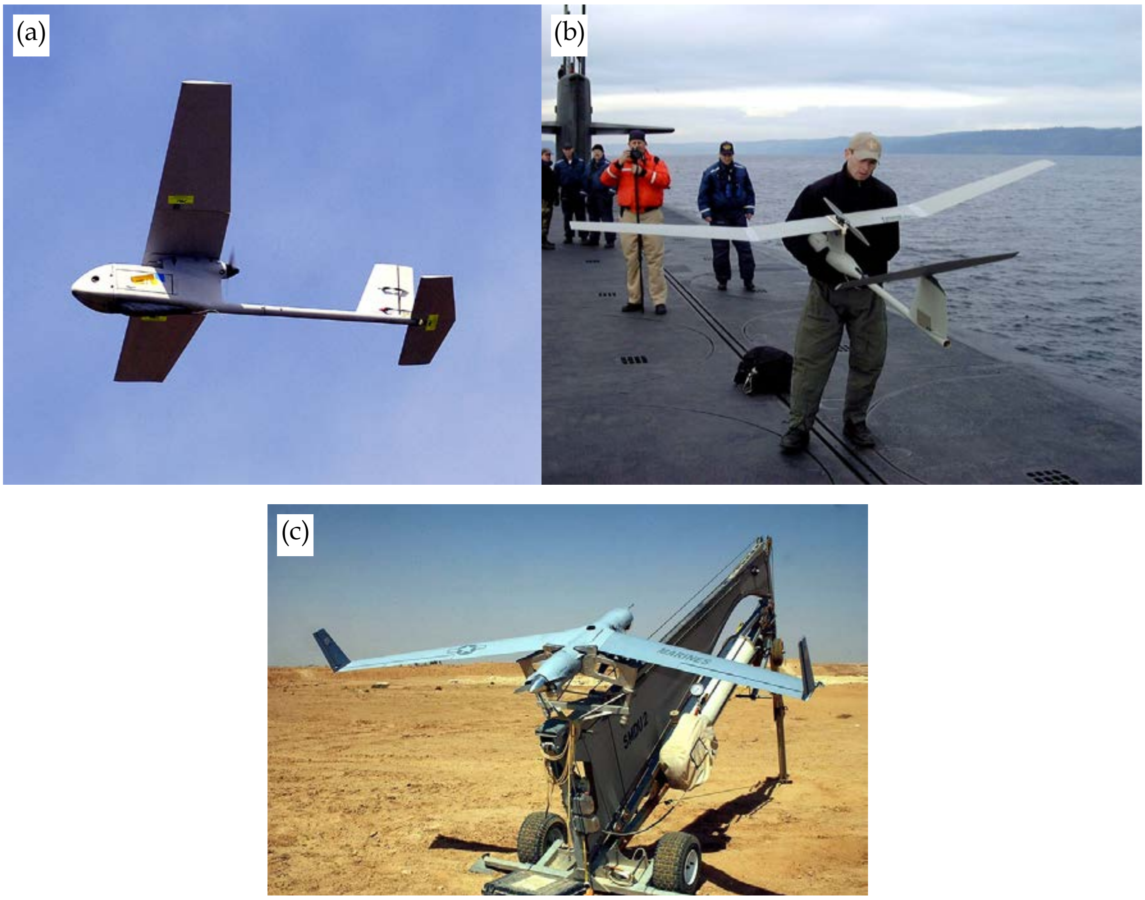


Figure 16 Typical small, tactical UAS for which the flyability analysis described here could be applied: (a) a UAS used in a demonstration at the US Air Force Academy in 2006 (US Air Force photograph by Dennis Rogers, available at http://www.af.mil/shared/media/photodb/photos/060801-F-0000D-002.jpg); (b) a Pointer UAS used during an exercise onboard the USS Alabama (US Navy photograph by Master Chief Petty Officer Daniel J. Niclas, available at http://www.af.mil/shared/media/photodb/photos/051118-N-9999N-005.jpg); and (c) the ScanEagle UAS on its launcher (US Marine Corp. photograph by Gunnery Sgt. Shannon Arledge, available at http://www.usmc.mil/marinelink/image1.nsf/Lookup/2005417115454). Images reprinted with permission.

The flyability of the UAS was evaluated by comparing the wind-speed criterion with the maximum wind speed in the ABL at each horizontal grid point for each hour of each day during the period of 1 January 2007 to 31 May 2010. The flyability values at each location were then averaged over all hours of the day and over all days within each season in the sample period considered. This yielded the results shown in Figure 17, where the terrain contours, coastlines, and national boundaries are also displayed. Unsurprisingly, the relatively mild conditions predominant in Arizona during most of the year resulted in high levels of flyability across the region, with only slight reductions over mountainous terrain. In Winter (Figure 17(a)), however, reduced levels of flyability were seen over a significant portion of the region.

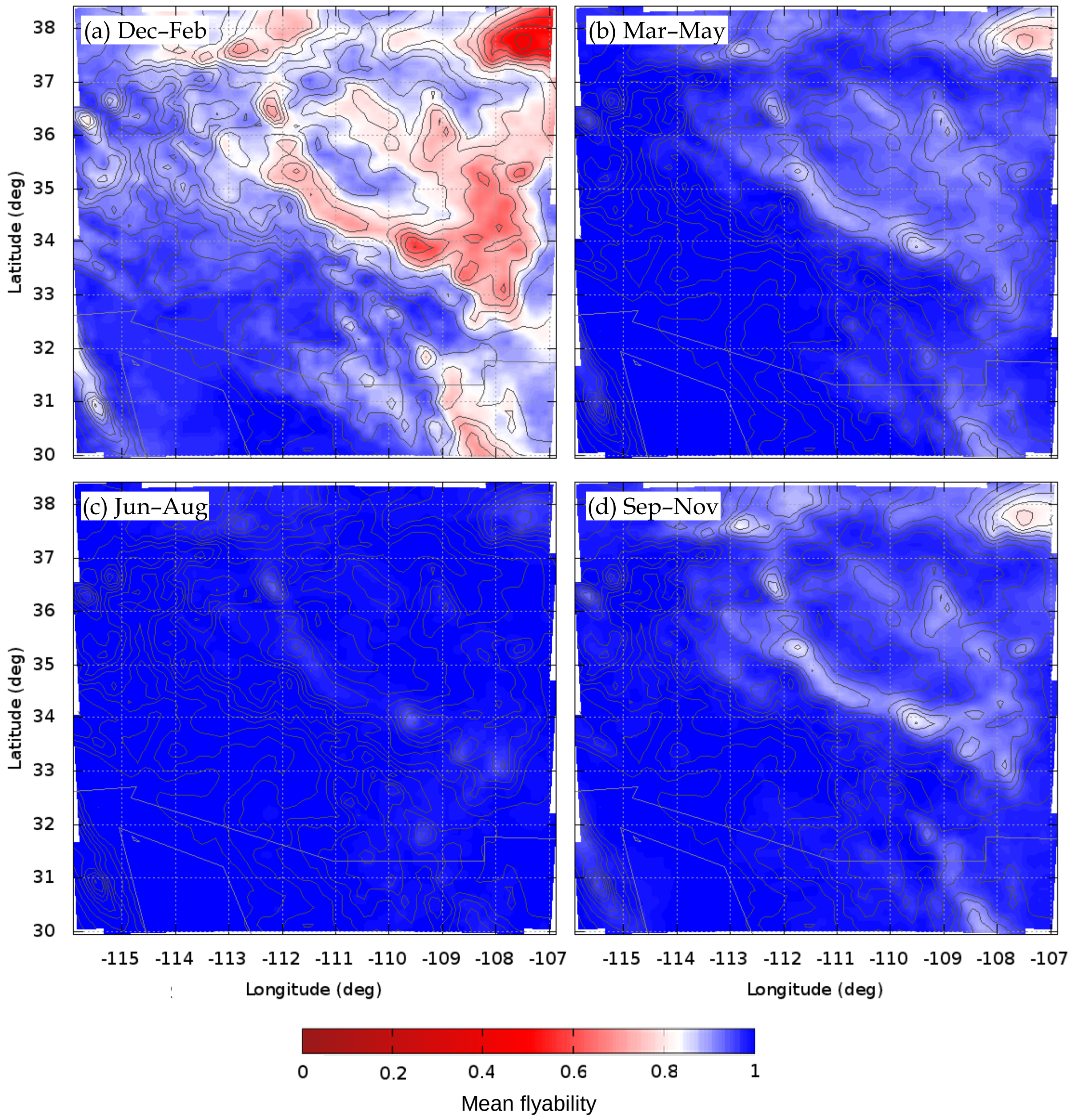


Figure 17 Mean flyability of a small UAS with a cruise speed of 20 m/s over the period from 1 January 2007 to 31 May 2010 in the region of Arizona, evaluated on a seasonal basis

This evaluation yielded the mean flyability of a small UAS through the entire ABL at each horizontal location; however, UAS are generally flown within specific altitude ranges and often with an airspace ceiling. Thus, another useful measure of flyability could be evaluated by restricting the analysis to a chosen flight altitude. If this were desired, the 14-m/s limit for flyability could be compared with the wind speed at the relevant operating altitude or altitude range (*e.g.*, 1000 m absolute altitude, 1000 m AGL, or 900–1100 m AGL, which would be typical of the aircraft shown in Figure 16). Maps similar to those shown in Figure 17, but valid for a specific altitude range, could thus be obtained.

In many instances, mean or 90%-CFL flyability as a function of location and altitude is not the sole parameter of interest. An alternative view of the data may be desirable if one wishes to understand the variability in the aircraft's flyability throughout a given region as a function of time of the year. To accomplish this, the flyability values computed previously for each day from 1 January 2007 to 31 December 2007 were averaged across the region (across grid locations) and over all hours of the day on a day-by-day basis. The results are shown in Figure 18.

Values of spatially averaged flyability as low as 0.2 were found to occur during the Winter months in Arizona. This indicates that conditions over the majority of the region would be unsuitable for UAS operations on some days of that period; however, the running average of daily flyability values (evaluated for ten-day windows of time) indicates a uniformly high mean level of flyability throughout the year, consistent with the results shown in Figure 17.

Although the results shown in Figure 17 were for a single historical year (2007), by extension, any other year might be expected to have a similar number of days on which an aircraft of the type considered would be largely unflyable in the Arizona region. This assumption could be tested by using the DEDS to make daily flyability assessments for each

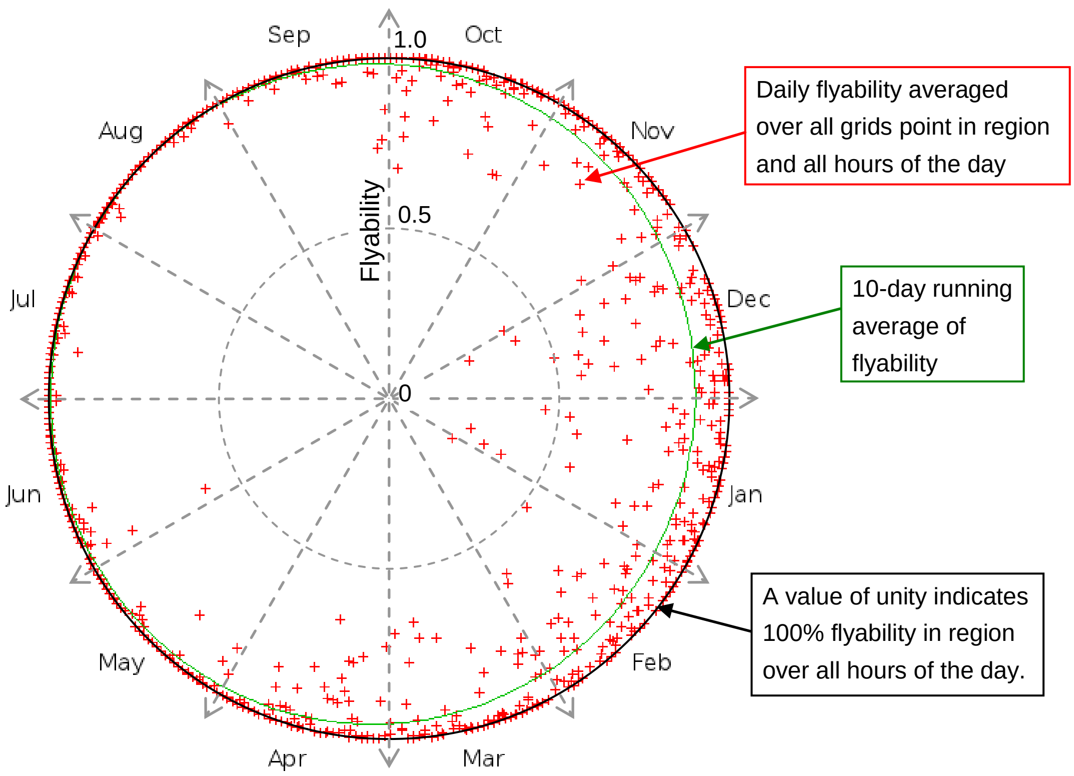


Figure 18 Daily flyability of a small UAS with a cruise speed of 20 m/s in the region of Arizona, evaluated by averaging the values across the region. The period covered is from 1 January 2007 to 31 December 2007.

year from 2007 up to the present. Such an assessment would span six years (as of this writing) and provide a significant level of trust in the predictive value of the result.

3.4 Other Performance Measures

In this analysis, UAS flight availability or “flyability”, one determinant of the potential utility of a particular UAS in a particular region, was assessed. The effects of atmospheric conditions on an ISR platform’s sensors and communications could be included by considering additional weather-dependent factors (*e.g.*, cloud-cover and other visibility measures).

4. Future Development

4.1 Improvements to Current Capabilities

4.1.1 Terrain Data

In late 2008, an enhanced version of the post-processed SRTM data, SRTM Version 4 or SRTM4, was released [26]. The dataset utilises improved interpolation and void-filling strategies and covers a larger proportion of the globe than does the dataset currently available on the DEDS, SRTM3 [28]. It is recommended that any future improvements to the DEDS terrain data focus on replacing the existing terrain dataset with SRTM4 and on improving the format conversions applied to the data.

At a minimum, terrain data with a resolution of 3 arcsec (DTED-1 data, as currently supplied by the DEDS) is required for use in CBRN-dispersion modelling; and DTED-2 data, which has a resolution of 1 arcsec, is desired over Australian capital cities. Acquisition of the latter is a goal for the future development of the DEDS.

4.1.2 Meteorological Data and Modelling

GFS data for the period November 2006 — June 2009 may be requested from NOAA to complete the DEDS's 24-hr hindcasting capability within that period; however, this is not a quick or efficient process and thus has not been undertaken as yet. Data for up to ten previous years is available upon request from NCAR, as part of its Reanalysis Project [52]. Hindcast weather data at lower resolution and quality is also obtainable for as far back as 1948 at no cost.

As described in §2.2.2.4, historical GFS data may be obtained for future augmentation of the DEDS data store. The existing archived data (dating from November 2006) is useful for platform-performance evaluations, such as the one described in §3; however, applications for which a more complete statistical view of weather conditions is necessary would require additional historical data.

The authors have not assessed the effect that an upgrade to the latest version of WRF (Version 3.1 [76]) would have on the quality of the mesoscale meteorological products provided by the DEDS, because an upgrade is deemed unnecessary at present.

4.1.3 Building-Geometry Data

Additional building-geometry data may be purchased from one of several commercial providers; and software techniques, currently the topic of research [77], may be used in future to produce data for new regions from satellite or aircraft imagery. At present, these are not priorities; thus their addition to the DEDS has not been undertaken.

4.1.4 Population-Density Data

Several sources of error associated with the population-density data available from the DEDS are described in §2.2.4. The population model is static; however, regular updates to the data could be acquired from the ABS. Alternatively, a dynamic model of population, such as that used by the ABS in the years between censuses and to create a "population clock" [78], could be employed. The ABS uses a stochastic model of population growth, which incorporates the rates of birth, death, and immigration, to improve population estimates.

The accuracy of the population-density data is also influenced by the size of the sampling regions used to derive it. In order to produce the best possible population-density model, it is essential to use sampling regions of the smallest size possible. In future, this could be achieved by using census Collection Districts [63], rather than Local Government Areas, to create a regular grid of population density with less error than results from the method used currently by the DEDS.

Some error in the current DEDS population-density model also resulted from changes in local-government boundaries between the times when the census data was collected and when the boundaries were published by the ABS. Future updates to the population model should ensure that sampling boundaries and population estimates are better correlated.

Finally, the data produced by the ABS does account for the effect of time of day, day of the week, or time of the year. This means that the current DEDS population model does not accurately capture the dynamics of the population, *e.g.*, the transport of people to and from work or the differences in population distributions on weekends and weekdays. This error could be minimised by adding a model of population as a temporally and spatially dependent diffusive process. Such models are the subject of on-going research [79, 80].

4.2 Extension to Microscale Weather Modelling

4.2.1 Existing Capability *vs.* Microscale-Modelling Requirements

The DEDS provides mesoscale weather modelling, typically on a grid of 6 km × 6 km or 12 km × 12 km, or down to 1 km × 1 km if selected through the API. Figure 19 shows an example of the mesoscale weather modelling generated by the DEDS and how cloud-like structures can be represented; however, the scale and resolution of the data are unsuitable for realistic representations of relatively small, organised atmospheric structures. As illustrated in Figure 19, mesoscale modelling generally captures features extending several degrees latitudinally and longitudinally, where each degree of longitude is equivalent to 79 km at the latitude pictured and each degree of latitude is equivalent to 111 km [28].

Organised flow structures commonly encountered in the atmospheric boundary layer are shown in Figure 20, which also provides brief descriptions of their origins. The resolution necessary to characterise these large-scale turbulent structures is obtainable with computational fluid dynamics (CFD) [82-84] and other high-resolution forms of atmospheric modelling [85, 86]. Such computations permit the structures to be realistically represented, both

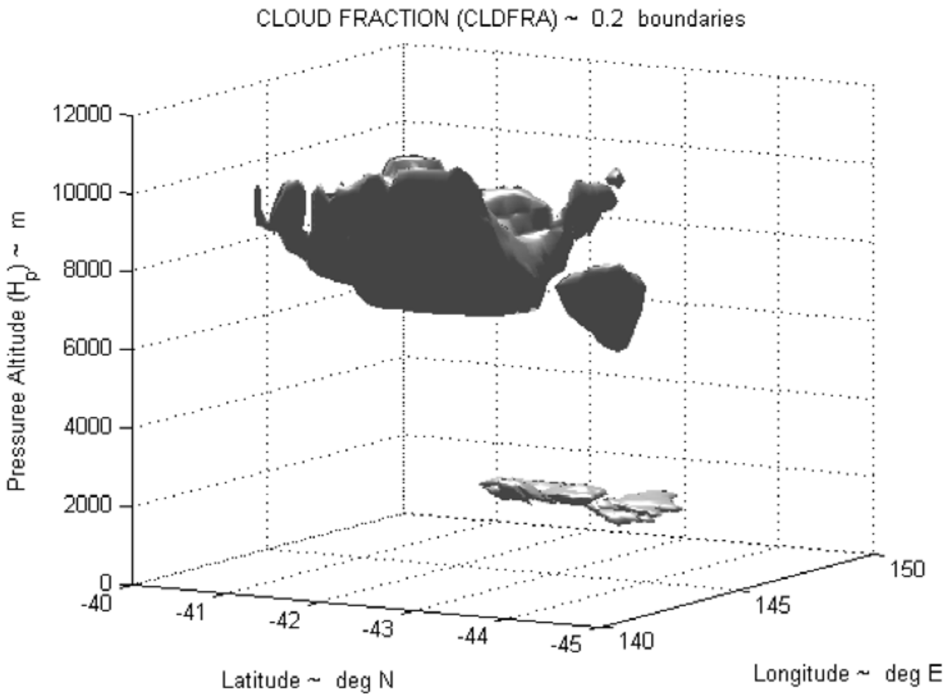


Figure 19 Visualisation of a cloud-like structure constructed from the output of the mesoscale weather model used by the DEDS by placing a solid surface where the cloud fraction (water-vapour density) in the atmosphere is greater than 20%. The pressure altitude (H_p) used on the vertical axis is equivalent to geometric altitude on a "standard" day [81].

numerically and graphically, in complex simulations requiring a higher level of detail than is supplied by the DEDS, a goal shared by US defence researchers [1]. The availability of such results could significantly enhance simulations used in the DSTO S&T program and many that DSTO provides to the ADF and the Defence Materiel Organisation.

To address this need, the weather-modelling capability of the DEDS has been augmented through with a high-resolution (microscale) atmospheric model relying on large-eddy simulation (LES) [82, 87], a CFD approach. AOD personnel undertook the work, with ADSO sponsorship of a DSMCP project in FY 2010/2011, to support the engineering- and science-focussed flight simulators it produces. Realistic environmental modelling is critical for sensor modelling, including radar and forward-looking infrared (FLIR) sensor emulation. The visual realism of flight simulators can also be greatly increased by graphical displays of clouds and storms, and the realism of their "feel" enhanced by the inclusion of pressure fronts, wind (mean and gust), and convective and terrain-induced lift.

Microscale meteorological modelling will benefit an Aerospace Division project investigating the use of hybrid propulsion and advanced power management on tactical UAS. The aim of the project, part of a DSTO Corporate Enabling-Research Program Initiative on Signatures, Materials, and Energy, is to enhance the capabilities of small, electrically powered UAS by increasing their range and endurance. Environmental-energy-harvesting techniques,

(a)

(b)

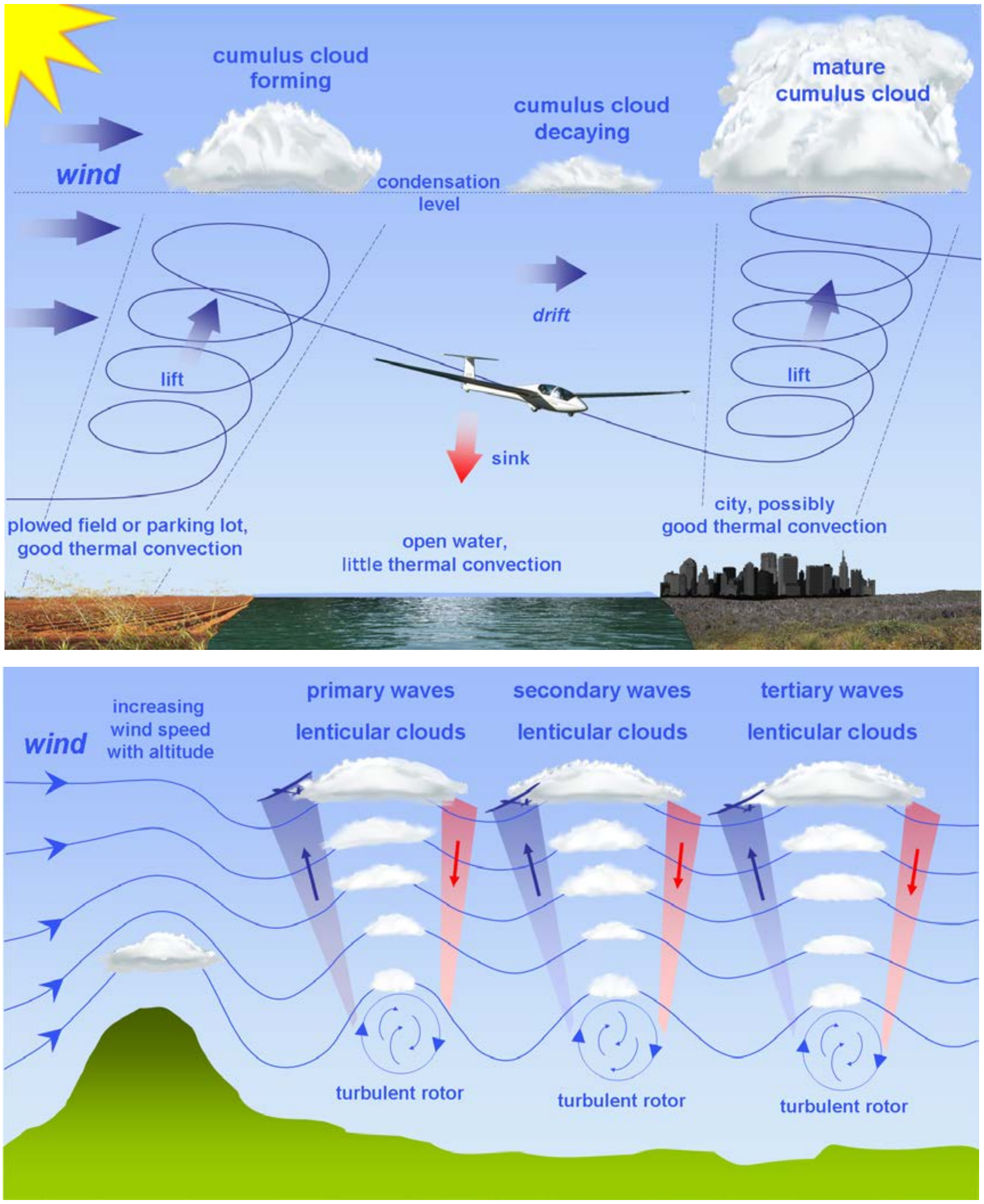


Figure 20 (a) An illustration of the formation and decay of cumulus clouds, which are generated by the upward motion of air warmed by solar heating of the ground surface. Also indicated are their response to cross-wind and the manner in which an aircraft may exploit convective (or thermal) updrafts to increase its altitude while conserving on-board energy stores (soaring). (b) An illustration of a phenomenon known as 'mountain wave.' The flow of air (wind) over a mountain generates a series of waves and turbulent rotors (large-scale vortices) downstream and pushes air above the condensation level, where colder temperatures result in the formation of lenticular (lens-shaped) clouds. Several air crashes have been attributed to the occurrence of turbulent rotors.

such as autonomous thermal soaring and solar collection, and the application of novel power sources are being explored through modelling and simulation, bench testing, and flight trials. Mesoscale modelling can be used in estimating the aircraft performance achievable through the use of such technologies [2, 88], though high-fidelity flight simulations incorporating atmospheric data obtained with microscale modelling can yield more precise evaluations [75]. Microscale modelling can also better assist in post-trial analysis [74].

4.2.2 Microscale-Modelling System

The modelling system developed by AOD personnel, known as Cyclone, is not currently part of the DEDS. Though each software package relies on global meteorological data and numerical models supplied by NOAA, the DEDS utilises RASP and Version 2.2 of WRF [49-51]; while the new modelling system replaces RASP with software created by DSTO researchers (with contractor assistance) that executes Version 3.1 of WRF [76]. The later version of WRF not only has the option of mesoscale modelling using computational methods nearly identical to those in Version 2.2, but also enables the use of LES with computational grid points spaced as little as 30 m apart.

WRF performs LES modelling in a particular region of interest with user-defined, nested computational grids stepping down from the lowest resolution (largest grid spacing), present in the outermost grid, to the highest resolution (smallest grid spacing) specified by the user. Each successive grid has a spacing that is a fraction (*e.g.*, one-half or one-third) of that of the previous level [82, 84]. A mesoscale computation is performed in the outermost grid to provide boundary conditions (forcing) for the sub-grid(s) on which LES computations are performed; and advection and diffusive processes across the grid boundaries result in the flow of information from the outer grid to the higher-resolution grid(s).

A "buffer" of additional points between the boundaries of adjacent grids having different resolutions is necessary to avoid the propagation of numerical artefacts arising from grid interactions into the innermost region of interest. The spatial extent of the outermost grid relative to that of the region over which the highest-resolution results are desired (the region of interest to the user) depends on the number of nesting levels defined by the user as well as the number of buffering grid points.

Figure 21 provides an example of a computational structure that would be generated if a user requested an outer grid having points every 4 km and three successively finer grids, each with one-half the spacing of the previous (coarser) grid; however, by default, DSTO's implementation of microscale modelling utilises a structure in which each successively finer grid has one-third the spacing of the previous grid. The number of buffering points shown in Figure 21 (four) is also only illustrative. Testing of the LES-modelling software indicated that at least eight buffering points are required.

Version 3.1 of WRF also permits simulations in which the innermost region of interest can move. This facility, originally intended for efficient, high-fidelity simulation of hurricanes (or cyclones), has been proposed by DSTO to permit simulation of microscale atmospheric effects

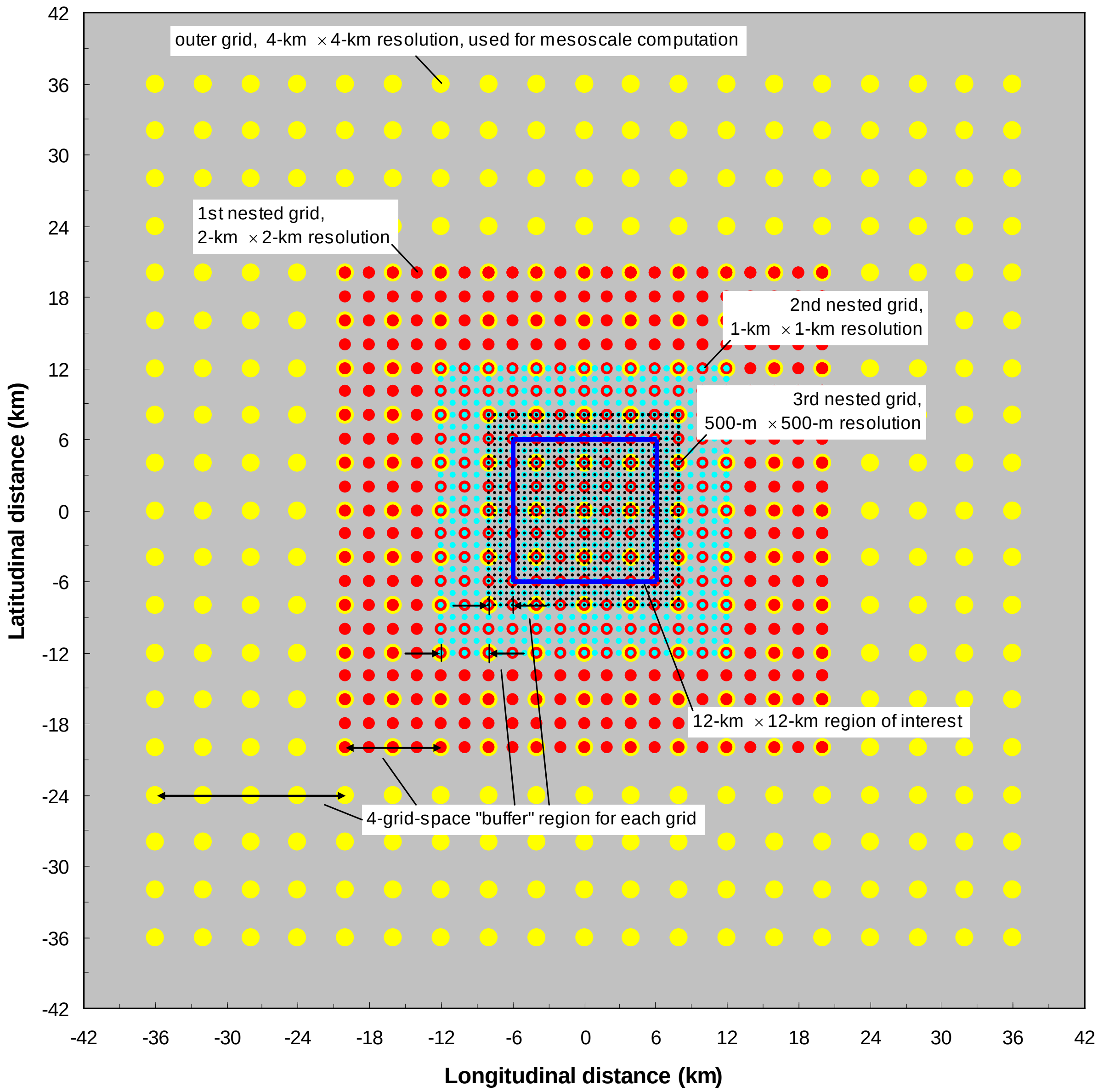


Figure 21 Illustration of nested computational grids ranging from 4-km × 4-km to 500-m × 500-m resolution, with four grid spaces separating the boundaries of each successively finer grid. The region of interest is 12 km × 12 km in size, centred at (0, 0), and is shown with a blue line.

around a mobile entity, such as an aircraft, and may be implemented in future updates of the DSTO software.

4.2.3 Integrating Microscale Modelling into the DEDS

Accessing microscale meteorological modelling through the DEDS interface would seem to be an attractive option, and the DEDS interface could be adapted with only a moderate level of additional development to incorporate the software used to execute the more recent version of

WRF. The required modification would entail replacing RASP with the software developed under the ADSO-sponsored project conducted by AOD personnel and adapting the capability that exists in the DEDS software for the user to select ranges of dates for modelling. In addition, a separate job type for microscale weather modelling could be created in the DEDS software (much as 'Aviation Meteorology' and 'Terrain Height' are separate job types from 'Mesoscale Weather'); and the DEDS GUI could be redesigned to permit the user to specify the nested computational grids used with the LES option of WRF, Version 3.1, when the new job type is selected.

One significant problem arises from this prospect. To maintain reasonable run times, the computational intensity of microscale modelling would require more powerful microprocessors than are necessary for the existing version of the DEDS. With the server hardware on which the DEDS is currently hosted, about 1 hr is required to perform mesoscale weather modelling for a 24-hr period in a region covering 200 km × 200 km with a 6-km × 6-km grid. In contrast, the execution time would be roughly 270 hr (11 days) for the same computer hardware performing an LES computation covering a 24-hr period with a nested computational grid of 375 m × 375 m in the same region. An outer grid with a spacing of 6 km × 6 km, on which a mesoscale computation would be performed, and four nested grids with resolutions of 3 km × 3 km, 1500 m × 1500 m, 750 m × 750 m, and finally 375 m × 375 m would be required. The outer grid would cover about 380 km × 380 km, as this would provide the minimum number of buffering grid points (eight) between adjacent boundaries of grids having different resolutions to avoid numerical artefacts in the innermost 200-km × 200-km region.

Furthermore, the data-handling and -storage overheads involved in managing the very large data files generated by microscale modelling would require hardware beyond that commonly needed to utilise the existing DEDS software. For the example used above, a 9-GB NetCDF file would be produced for every hour of the microscale simulation, whereas a comparable file generated for a mesoscale computation by the DEDS is 34 MB in size. Indeed, microscale modelling of areas of sufficient size to be practical in many DSTO applications requires the use of cluster computing to distribute the processing load. Although cluster computing support is built into WRF Version 3.1, the DEDS infrastructure is not specifically designed to make use of it and may require re-engineering to do so.

4.2.4 Summary of Microscale-Modelling Requirements

Any server system employing a version of the DEDS with a microscale-weather-modelling option would be required to utilise more powerful (and more expensive) processing units and to have much greater data-storage capacity than does the computer on which the DEDS is currently hosted at DSTO – unless the user(s) of that system chose to disregard its microscale-meteorological-modelling capability and utilised only the data-processing types available in the original DEDS software. This is a reasonable alternative because in many situations mesoscale results are sufficiently detailed; though, if that is the case, the DEDS software would be more simply (and immediately) employed in its unaltered form.

Because of the disparities between the requirements of the modelling software utilised by the DEDS and that created for microscale meteorological modelling (Cyclone), the *status quo*, in which the two software systems are maintained on separate servers and access to them is gained through separate interfaces, is judged by the authors to be the best solution for the foreseeable future. When mesoscale weather modelling is sufficient, or the other types of environmental data supplied by the DEDS are needed, the DEDS can be used; and only when microscale weather modelling is specifically required would the newly developed system be used.

4.3 Incorporation in Operational Systems

As mentioned in §1.3.2.1, the DEDS has been designated as a component of the ADSO DSE Baseline Program, though not (necessarily) in a forecasting capacity. As discussed in §2.6.1, in the event that the DEDS software undergoes a future transition into service outside DSTO, particularly if for forecasting, it is recommended that the BoM or other subject-matter experts be enlisted to determine how to best use the mesoscale meteorological model it employs and to provide guidelines to prevent its misuse.

Furthermore, the accuracy of a forecasting system would need to be evaluated for specific areas of interest through detailed comparisons between the model output and observed data; and an approach employing model output statistics (MOS) could be used to improve the region-specific forecasting fidelity [89]. MOS methods combine the output of numerical weather predictions (forecasts), such as those that could be produced using the DEDS, with statistical models based on detailed historical measurements of conditions in a specific region, essentially tailoring the output of a synoptic or mesoscale prediction to better reflect local idiosyncrasies. These methods significantly improve local forecasts, but require particular meteorological expertise and access to ground stations, such as those utilised by the BoM, to provide an appropriate local statistical model [89].

Any forecasting capability would also require continual and immediate access to the global weather data provided by NOAA; and, this would necessitate uninterrupted internet access and software modifications to handle connection problems. It would be prudent to arrange access to one of NOAA's non-public operational servers to ensure high availability and to employ logic in the GFS query so that if one server were unavailable, another could be accessed, a level of complexity that was unnecessary for the present version of the DEDS. Issues related to IP, licensing, certification, and accreditation, all necessary considerations for any possible incorporation of the DEDS into an operational system, are discussed in more detail in §2.5 and §2.6.

5. Conclusion

5.1 DEDS Capability

5.1.1 Raw Data and Data Processing

The DEDS supplies data describing the physical environment, including mesoscale (regional) atmospheric modelling, high-resolution terrain data, building-geometry data for Australian capital cities, and Australian population-density data. The raw data has been obtained from reliable, high-quality sources; and the software automates the on-going retrieval of freely available meteorological source data, with built-in correction for errors and exceptions. The global meteorological data, which is needed for historical regional weather modelling (hindcasts), continues to be downloaded on a daily basis, with the archived data covering the period from November 2006 to the present.

The primary component of new technology contained in the DEDS software is a system incorporating scheduling, execution, and integration/conversion tools. End-users can define their region(s) of interest and request data processing (*e.g.*, mesoscale hindcasts or terrain-data conversions) through a web-based interface on computers connected through a network to a server on which the DEDS is installed. The processed data can be delivered in a variety of formats, either through the graphical interface or through a programming interface, which can be accessed by other simulations requiring environmental data as input.

The DEDS also provides a facility enabling users to create analytical products on the server; thereby eliminating the need for the transfer of large amounts of data between the server computer and a user's computer. Furthermore, the design of the DEDS software and its administration within DSTO permit platform-, sensor-, and weapons-performance parameters to be incorporated into analyses executed on the server. This is an efficient use of staff and computer resources and supports the handling of security-sensitive information.

The server software is robust, relatively easy and inexpensive to administer, and simple to incorporate in end-user simulations and studies. It can also be cloned to provide multiple systems with different security classifications or for separate user groups; however, implementation on systems at higher levels of classification would require certification of the software that has not yet been undertaken.

5.1.2 Meteorological Modelling

The DEDS provides a niche modelling capability required by DSTO at very low cost (*i.e.*, only the maintenance of the system) and supports real-time and constructive simulations with hindcast data. The meteorological model used by the DEDS permits atmospheric conditions to be resolved at the mesoscale (*i.e.*, on a grid of 6 km × 6 km, typically). The DEDS has not been designed as a forecasting tool and in no way replaces the forecasting service provided to the ADF (and to parts of DSTO) by the BoM.

Finally, if meteorological data is required at higher resolution than the DEDS supplies, DSTO has a facility available to carry out such modelling, as described in §4.2. If appropriate, that system could be incorporated into the DEDS software; though, at present, this development is judged unnecessary and in some ways undesirable and thus has not been undertaken.

5.2 Outcomes for Defence

The DEDS is a valuable Defence asset because it provides re-usable environmental data, including meteorological modelling results, and enables high-fidelity simulations and analyses of platform performance and vulnerability, as well as operational studies in which weather, climate, terrain, built structures, and/or population density may be significant factors. The system can also support real-time and constructive simulations for training, experimentation, and mission rehearsal using hindcast (historical) weather data.

As described in this report, the DEDS has been utilised by DSTO researchers for scientific analysis of contaminant dispersion through complex, built environments and in an aircraft-accident investigation. Some of its capabilities to inform platform-performance studies were also demonstrated through a statistical analysis of historical weather conditions over the course of several years. Graphical representations indicating mean flyability as a function of location and season or day of the year were presented for an aircraft typical of small surveillance UAS. If desired, greater predictive certainty could be gained by performing the computations with the full historical weather dataset available through the DEDS. This would, at present, yield means over six years and significantly enhanced statistical validity. Such considerations could be important if one wished to predict the performance of a platform in a region for which little operational experience was available. Although only one flyability condition was assessed here, the demonstrated methodology is extendable to evaluations of other effects that may degrade the performance of a UAS or its sensors (*e.g.*, rain, icing, and cloud cover).

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Appendix A: Output Meteorological Parameters

Table A.1 provides a list of the one-hundred and sixty-eight variables output by the RASP/WRF model when a 'Mesoscale Weather' data-retrieval request is made by a user of the DEDS. This is the default list of variables produced when WRF is executed through the DEDS GUI. Slightly different combinations of variables may result from runs made with user-specified settings of the WRF model via the DEDS API; and descriptions of any additional variables obtained in that way are provided in Reference [48] and in other on-line documentation for WRF.

Thirty additional variables are computed and output to a separate file when 'Aviation Meteorology' is requested, along with replicates of sixteen of the variables output with a 'Mesoscale Weather' request. The variables output in response to an 'Aviation Meteorology' request are listed in Table A.2.

The following commands may be used in Mathworks MATLAB™ to access data from a NetCDF file generated in a 'Mesoscale Weather' or 'Aviation Meteorology' run. The first line of the example code given below opens an output file generated by the DEDS for 1200 LST and assigns it an identification number (`ncid`). The variable identifier (`varid`) associated with, for example, the variable representing the horizontal wind speed in the longitudinal direction (`U`) is then determined; and a variable array (`Udata`) is created in the MATLAB workspace by reading the data with that identifier from the file.

```
ncid = netcdf.open('raspwrfout_d02_1200LST_timestamp.netcdf','NOWRITE');
varid = netcdf.inqVarID(ncid,'U');
Udata = netcdf.getVar(ncid,varid);
```

Any of the other variables listed in Tables A.1 and A.2 may be accessed in an analogous way.

Table A.1 Variables output to NetCDF files when a user of the DEDS requests 'Mesoscale Weather' data retrieval

Variable name	Variable description	Coordinates	Units
ALBEDO	Albedo	latitude/longitude	-
BLCLOUDPCT[1]	BL cloud cover	latitude/longitude	%
BLCWBASE[1]	BL explicit cloudbase	latitude/longitude	ft AGL
BLTOPVARIAB[1]	BL top uncertainty/variability (for +1 °C)	latitude/longitude	ft
BLTOPWINDDIR[1]	BL top wind direction	latitude/longitude	degrees
BLTOPWINDSPD[1]	BL top wind speed	latitude/longitude	kt
BLWINDDIR[1]	BL wind direction	latitude/longitude	degrees
BLWINDSHEAR[1]	BL vertical wind shear	latitude/longitude	kt
BLWINDSPD[1]	BL wind speed	latitude/longitude	kt
BSRATIO[1]	Buoyancy/shear ratio	latitude/longitude	-
CANWAT	Canopy water	latitude/longitude	kg/m^2
CAPE[2]	Convective atmospheric potential	latitude/longitude	J/kg

[1] Automatically output in graphical form (a PNG file) and in a plain text file on an hourly basis.

Variable name	Variable description	Coordinates	Units
	energy		
CF1	2nd-order extrapolation constant	-	-
CF2	2nd-order extrapolation constant	-	-
CF3	2nd-order extrapolation constant	-	-
CFN	Extrapolation constant	-	-
CFN1	Extrapolation constant	-	-
CFRACH	eta 2D cloud fraction – high	latitude/longitude	-
CFRACL	eta 2D cloud fraction – low	latitude/longitude	-
CFRACM	eta 2D cloud fraction – mid	latitude/longitude	-
CLDFRA	Cloud fraction	latitude/longitude/height	-
COSALPHA	Local cosine of map rotation	latitude/longitude	-
CWM	Total condensate mixing ratio	latitude/longitude/height	kg/kg
DBL[2]	BL depth	latitude/longitude	ft
DN	d(eta) values between full (mass) levels	height	-
DNW	d(eta) values between full (*w*) levels	height	-
DWCRIT[2]	Depth of critical updraft strength (AGL H_{crit})	latitude/longitude	ft
DZS	Thicknesses of soil layers	depth	m
E	Coriolis cosine latitude term	latitude/longitude	s^{-1}
F	Coriolis sine latitude term	latitude/longitude	s^{-1}
FNM	Upper weight for vertical stretching	height	-
FNP	Lower weight for vertical stretching	height	-
GLW	Downward longwave flux at ground surface	latitude/longitude	W/m^2
GRAUPELNC	Accumulated total grid-scale Graupel	latitude/longitude	mm
GRDFLX	Ground heat flux	latitude/longitude	W/m^2
H	Geopotential height with respect to the surface of the WGS-84/EGM96 geoid[3]	latitude/longitude/height	m
HBL[2]	Height of BL top	latitude/longitude	ft
HFX	Upward heat flux at the surface	latitude/longitude	W/m^2
HGT	Terrain height	latitude/longitude	m
HWCRIT[2]	Height of critical-updraft strength (H_{crit})	latitude/longitude	ft
ISLTYP	Dominant soil category	latitude/longitude	-
ITIMESTEP	-	-	-
IVGTYP	Dominant vegetation category	latitude/longitude	-
LANDMASK	Land mask (1 for land, 0 for water)	latitude/longitude	-
LAT_LL_D	Latitude lower left, massless point	-	degrees
LAT_LL_T	Latitude lower left, temperature point	-	degrees
LAT_LL_U	Latitude lower left, *u* point	-	degrees
LAT_LL_V	Latitude lower left, *v* point	-	degrees
LAT_LR_D	Latitude lower right, massless point	-	degrees
LAT_LR_T	Latitude lower right, temperature point	-	degrees
LAT_LR_U	Latitude lower right, *u* point	-	degrees
LAT_LR_V	Latitude lower right, *v* point	-	degrees
LAT_UL_D	Latitude up left, massless point	-	degrees

[2] Automatically output in graphical form (a PNG file) and in a plain text file on an hourly basis.
[3] See [90].

Variable name	Variable description	Coordinates	Units
LAT_UL_T	Latitude upper left, temperature point	-	degrees
LAT UL U	Latitude up left, *u* point	-	degrees
LAT_UL_V	Latitude up left, *v* point	-	degrees
LAT_UR_D	Latitude up right, massless point	-	degrees
LAT_UR_T	Latitude up right, temperature point	-	degrees
LAT_UR_U	Latitude up right, *u* point	-	degrees
LAT_UR_V	Latitude up right, *v* point	-	degrees
LH	Latent heat flux at the surface	latitude/longitude	W/m^2
LON_LL_D	Longitude lower left, massless point	-	degrees
LON_LL_T	Longitude lower left, temperature point	-	degrees
LON_LL_U	Longitude lower left, *u* point	-	degrees
LON_LL_V	Longitude lower left, *v* point	-	degrees
LON_LR_D	Longitude lower right, massless point	-	degrees
LON_LR_T	Longitude lower right, temperature point	-	degrees
LON_LR_U	Longitude lower right, *u* point	-	degrees
LON LR V	Longitude lower right, *v* point	-	degrees
LON_UL_D	Longitude up left, massless point	-	degrees
LON_UL_T	Longitude up left, temperature point	-	degrees
LON_UL_U	Longitude up left, *u* point	-	degrees
LON_UL_V	Longitude up left, *v* point	-	degrees
LON UR D	Longitude up right, massless point	-	degrees
LON_UR_T	Longitude up right, temperature point	-	degrees
LON_UR_U	Longitude up right, *u* point	-	degrees
LON_UR_V	Longitude up right, *v* point	-	degrees
LU_INDEX	Land use category	latitude/longitude	-
MAPFAC_M	Map scale factor on mass grid	latitude/longitude	-
MAPFAC_U	Map scale factor on *u*-grid	latitude/longitude	-
MAPFAC_V	Map scale factor on *v*-grid	latitude/longitude	-
MU	Perturbation dry-air mass in column	latitude/longitude	Pa
MUB	Base-state dry-air mass in column	latitude/longitude	Pa
NEST_POS	-	latitude/longitude	-
OLR	Total outgoing longwave radiation	latitude/longitude	W/m^2
P	Perturbation pressure	latitude/longitude/height	Pa
P_TOP	Pressure top of the model	latitude/longitude	Pa
PB	Base-state pressure	latitude/longitude/height	Pa
PBLH	PBL height	latitude/longitude	m
PH	Perturbation geopotential height	latitude/longitude/height	m^2/s^2
PHB	Base-state geopotential height	latitude/longitude/height	m^2/s^2
POTEVP	Accumulated potential evaporation	latitude/longitude	W/m^2
PSFC	Surface pressure	latitude/longitude	Pa
Q2	QVAPOR at 2 m	latitude/longitude	kg/kg
QCLOUD	Cloud water mixing ratio	latitude/longitude/height	kg/kg
QFX	Upward surface-moisture flux at the surface	latitude/longitude	$kg/m^2/s$
QGRAUP	Graupel mixing ratio	latitude/longitude/height	kg/kg
QICE	Ice mixing ratio	latitude/longitude/height	kg/kg
QRAIN	Rain-water mixing ratio	latitude/longitude/height	kg/kg

Variable name	Variable description	Coordinates	Units
QSNOW	Snow mixing ratio	latitude/longitude/height	kg/kg
QVAPOR	Water-vapour mixing ratio	latitude/longitude/height	kg/kg
RAINC	Accumulated total cumulus precipitation	latitude/longitude	mm
RAINNC	Accumulated total grid-scale precipitation	latitude/longitude	mm
RDN	Inverse d(eta) values between full (w) levels	height	-
RDNW	Inverse d(eta) values between full (w) levels	height	-
RDX	Inverse x-grid length	-	-
RDY	Inverse y-grid length	-	-
RESM	Time weight constant for small steps	-	-
RHOSN	Snow density	latitude/longitude	kg/m^3
RQCBLTEN	Coupled Q_c tendency due to PBL parameterisation	latitude/longitude/height	Pa·kg/kg/s
RQVBLTEN	Coupled Q_v tendency due to PBL parameterisation	latitude/longitude/height	Pa·kg/kg/s
RTHBLTEN	Coupled theta tendency due to PBL parameterisation	latitude/longitude/height	Pa·K/s
SFCDEWPT[4]	Surface dewpoint temperature (2 m AGL)	latitude/longitude	°C
SFCSHF[4]	Surface heating	latitude/longitude	W/m^2
SFCSUNPCT[4]	Normalized surface solar radiation	latitude/longitude	%
SFCTEMP[4]	Surface temperature (2 m AGL)	latitude/longitude	°C
SFCWINDDIR[4]	Surface wind direction (10 m AGL)	latitude/longitude	degrees
SFCWINDSPD[4]	Surface wind speed (10 m AGL)	latitude/longitude	kt
SFROFF	Surface runoff	latitude/longitude	mm
SH2O	Soil liquid water	latitude/longitude/depth	m^3/m^3
SINALPHA	Local sine of map rotation	latitude/longitude	-
SMOIS	Soil moisture	latitude/longitude/depth	m^3/m^3
SNOPCX	Snow phase-change heat flux	latitude/longitude	W/m^2
SNOW	Snow–water equivalent	latitude/longitude	kg/m^2
SNOWC	Flag indicating snow coverage (1 for snow cover)	latitude/longitude	-
SNOWH	Physical snow depth	latitude/longitude	m
SNOWNC	Accumulated total grid-scale snow and ice	latitude/longitude	mm
SOILTB	Bottom soil temperature	latitude/longitude	K
SR	Fraction of frozen precipitation	latitude/longitude	-
SST	Sea-surface temperature	latitude/longitude	K
SWDOWN	Downward shortwave flux at ground surface	latitude/longitude	W/m^2
T	Perturbation potential temperature ($\theta - t_0$)	latitude/longitude/height	K
T2	Temperature at 2 m AGL	latitude/longitude	K
TC	Ambient static temperature	latitude/longitude/height	°C
TH2	Potential temperature at 2 m AGL	latitude/longitude	K
TIMES	LST of model output	-	-
TKE	Turbulent kinetic energy	latitude/longitude/height	m^2/s^2
TMN	Soil temperature at lower boundary	latitude/longitude	K

[4] Automatically output in graphical form (a PNG file) and in a plain text file on an hourly basis.

Variable name	Variable description	Coordinates	Units
TSK	Surface skin temperature	latitude/longitude	K
TSLB	Soil temperature	latitude/longitude/depth	K
U	x-wind component	latitude/longitude/height	m/s
U10	x-component wind speed at 10 m	latitude/longitude	m/s
UDROFF	Underground runoff	latitude/longitude	mm
UST	u_* in similarity theory	latitude/longitude	m/s
V	y-wind component	latitude/longitude/height	m/s
V10	y-component wind speed at 10 m	latitude/longitude	m/s
VEGFRA	Vegetation fraction	latitude/longitude	-
W	z-wind component	latitude/longitude/height	m/s
WBLMAXMIN[5]	BL maximum up/down motion, w_{BL}	latitude/longitude	cm/s
WSTAR[5]	Thermal updraft velocity, W^*	latitude/longitude	ft/min
XICE	Sea-ice flag	latitude/longitude	-
XLAND	Land mask (1 for land, 0 for water)	latitude/longitude	-
XLAT	Latitude, South is negative	latitude/longitude	degrees N
XLAT_U	Latitude, South is negative	latitude/longitude	degrees N
XLAT_V	Latitude, South is negative	latitude/longitude	degrees N
XLONG	Longitude, West is negative	latitude/longitude	degrees E
XLONG_U	Longitude, West is negative	latitude/longitude	degrees E
XLONG_V	Longitude, West is negative	latitude/longitude	degrees E
XTIME	Time since simulation start	-	min
ZBLCL[5]	Overcast development cloudbase (BL CL)	latitude/longitude	ft
ZBLCLDIF[5]	Overcast development potential	latitude/longitude	ft
ZETATOP	Zeta at model top	-	-
ZNU	Eta values on half (mass) levels	height	-
ZNW	Eta values on full (w) levels	height	-
ZS	Depths of centres of soil layers	depth	m
ZSFCLCL[5]	Cumulus cloudbase (surface lifted-condensation level)	latitude/longitude	ft
ZSFCLCLDIF[5]	Cumulus potential	latitude/longitude	ft
ZWBLMAXMIN[5]	MSL height of maximum up/down motion, w_{BL}	latitude/longitude	ft

Table A.2 Variables output to NetCDF files when a user of the DEDS requests 'Aviation Meteorology' data retrieval

Variable name	Variable description	Coordinates	Units
CLDFRA	Cloud fraction	latitude/longitude/height	-
C s	Ambient speed of sound	latitude/longitude/height	m/s
dT	Time since simulation start	-	s
dUdX	Spatial gradient of u in x-direction	latitude/longitude/height	s^{-1}
dUdY	Spatial gradient of u in y-direction	latitude/longitude/height	s^{-1}
dUdH	Spatial gradient of u in z-direction	latitude/longitude/height	s^{-1}
dVdX	Spatial gradient of v in x-direction	latitude/longitude/height	s^{-1}
dVdY	Spatial gradient of v in y-direction	latitude/longitude/height	s^{-1}
dVdH	Spatial gradient of v in z-direction	latitude/longitude/height	s^{-1}
dWdX	Spatial gradient of w in x-direction	latitude/longitude/height	s^{-1}
dWdY	Spatial gradient of w in y-direction	latitude/longitude/height	s^{-1}
dWdH	Spatial gradient of w in z-direction	latitude/longitude/height	s^{-1}
gamma	Specific-heat ratio	latitude/longitude/height	-

[5] Automatically output in graphical form (a PNG file) and in a plain text file on an hourly basis.

Variable name	Variable description	Coordinates	Units
GLW	Downward longwave flux at ground surface	latitude/longitude	W/m^2
H	Geopotential height with respect to the surface of the WGS-84/EGM96 geoid[6]	latitude/longitude/height	m
HGT	Terrain height	latitude/longitude	m
H_f	Freezing level (expressed as a geopotential height)[7]	latitude/longitude/height	m
H_p	Pressure altitude for a standard altimeter calibration[8]	latitude/longitude/height	m
L_d	Turbulence length scale in z-direction	latitude/longitude/height	m
L_e	Turbulence length scale in x-direction	latitude/longitude/height	m
L_n	Turbulence length scale in y-direction	latitude/longitude/height	m
mu	Dynamic viscosity[9]	latitude/longitude/height	Pa·s
Negm96	Undulation of the WGS-84/EGM-96 geoid above the WGS-84 ellipsoid[10]	latitude/longitude	m
OLR	Total outgoing longwave radiation	latitude/longitude	W/m^2
P_s	Static pressure	latitude/longitude/height	Pa
PSFC	Surface pressure	latitude/longitude	Pa
Psi_S	Local azimuth angle of the Sun, measured in the local horizontal plane with respect to true North, positive for rotation from North towards East[11]	latitude/longitude/height	rad
QVAPOR	Water-vapour mixing ratio	latitude/longitude/height	kg/kg
rho	Ambient density of moist air	latitude/longitude/height	kg/m^3
R_a	Ambient specific-gas constant	latitude/longitude/height	J/kg/K
Sigma_h	Turbulence intensity in any horizontal direction	latitude/longitude/height	-
Sigma_v	Turbulence intensity in vertical direction	latitude/longitude/height	-
SST	Surface sea temperature	latitude/longitude	K
SWDOWN	Downward shortwave flux at ground surface	latitude/longitude	W/m^2
Theta_S	Local elevation angle (altitude) of the Sun, measured normal to the local horizontal plane, positive for the Sun above the horizontal plane[12]	latitude/longitude/height	rad
T_d	Ambient dewpoint temperature[13]	latitude/longitude/height	K
T_f	Ambient frost-point temperature[14]	latitude/longitude/height	K

[6] See [90].
[7] Ibid.
[8] Ibid.
[9] Implements Sutherland's equation for air [91].
[10] Based on linear interpolation. Has a standard deviation of error less than 2 cm for all cases tested to-date [90].
[11] Based on the USNO NOVAS V3.0 software libraries [92].
[12] Ibid.
[13] Ibid.
[14] Implements the equations contained in [93, 94].

Variable name	Variable description	Coordinates	Units
`T_s`	Ambient static temperature	latitude/longitude/height	K
`U`	x-wind component	latitude/longitude/height	m/s
`U10`	x-component wind speed at 10 m	latitude/longitude	m/s
`U_w`	Relative humidity[15]	latitude/longitude/height	%
`V`	y-wind component	latitude/longitude/height	m/s
`V10`	y-component wind speed at 10 m	latitude/longitude	m/s
`W`	z-wind component	latitude/longitude/height	m/s
`XLAT`	Latitude, South is negative	latitude/longitude	degrees N
`XLONG`	Longitude, West is negative	latitude/longitude	degrees E
`Z_g`	Geometric height[16]	latitude/longitude/height	m

[15] Ibid. The relative humidity so defined is "over water", including in the range below freezing.

[16] Expressed with respect to the surface of the WGS-84/EGM96 geoid, or with respect to the ellipsoid or sphere for ellipsoidal or spherical earth models, respectively. At present, for lack of better data, geometric height is approximated in accordance with [90].

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19. ABSTRACT
A myriad of requirements exist within DSTO for rapid access to high-quality geospatial and meteorological data; and, with support from the Australian Defence Simulation Office, a software framework has been developed to efficiently and inexpensively serve such data for a variety of end-uses. The framework, implemented in software called the DSTO Environmental-Data Server (DEDS), includes facilities for distributed data warehousing and scheduled retrieval of published source data, as well as post-processing of data for format conversions, production of high-resolution models, and statistical analyses. Via the DEDS web interface or through its application programming interface, users can access: terrain-elevation data; historical regional-scale meteorological modelling; building-geometry data for Australian capital cities; and population-density data for Australia. Each data type is output to the user (or to the user's simulation) in a defined region with post-processing as requested by the user.

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